ENGINEERING DEPENDABLE PROTECTION — PART I
"A SIMPLE APPROACH TO SHORT-CIRCUIT CALCULATIONS"

This Handbook is one of a series prepared to help in the Engineering of Dependable Protection for Electrical Distributing Systems.

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WHY SHORT-CIRCUIT CALCULATIONS?

The protection for an electrical system should not only be safe under all service conditions but, to insure continuity of service, it should be selective as well. A selective system is one wherein only the faulted circuit is isolated without disturbing any other part of the system. Overcurrent protection devices should also provide short-circuit as well as low over-current protection for system components, such as bus, wire, motor controllers, etc.

To obtain safe, selective operation and assure that system components are protected from damage, we must first calculate the available fault current at various points in our electrical system.

Once the short-circuit levels are determined, we can specify proper interrupting requirements, selectively coordinate our system and provide component protection.

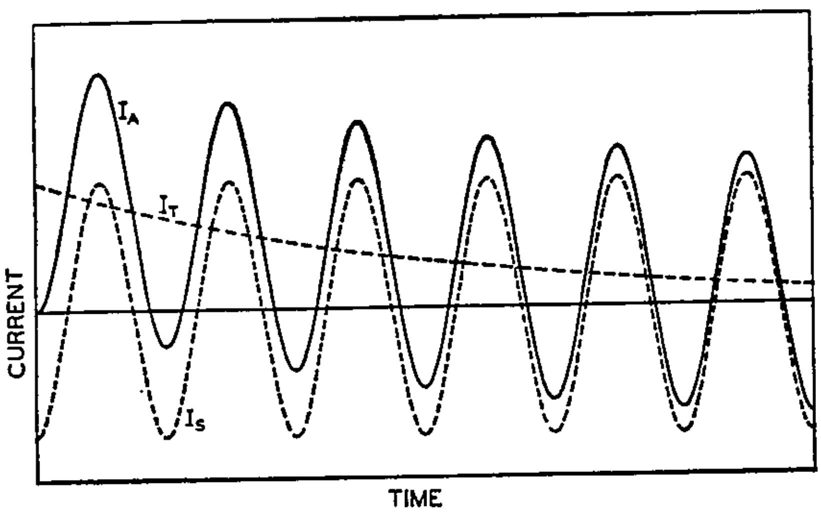
INTERRUPTING CAPACITY AND THE SHORT-CIRCUIT CURRENT

To begin, let's discuss interrupting capacity. Interrupting capacity can be defined as "the maximum short-circuit current that a protective device can safely clear."

The 1975 National Electrical Code requires adequate interrupting capacity in Sections 110-9 and 230-98.

> **Sections 110-9.** Interrupting Capacity. Devices intended to break current shall have an interrupting capacity sufficient for the voltage employed and for the current that must be interrupted.
>
> **Section 230-98.** Available Short-Circuit Current. Service equipment shall be suitable for the short circuit current available at its supply terminals.

Therefore, the first step is to determine the fault current levels of the system. An electric fault is usually an asymmetrical current that may be broken down into symmetrical (steady state) and transient components. A diagram of a typical fault broken down into its components is shown below.



TIME

I_A — Asymmetrical Current I_T — Transient Component
I_S — Symmetrical Component

The rms value of the symmetrical component may be determined using Ohm's Law. To determine the transient component, it is necessary to know the X/R ratio of the system. To obtain the X/R ratio the total resistance and total reactance of the circuit to the point of fault must be determined.

Low voltage fuses have their interrupting capacity expressed in terms of the symmetrical component of short-circuit current. They are given an rms symmetrical interrupting rating. This means that the fuse can interrupt any asymmetrical current associated with this rating. Thus, only the symmetrical component of short-circuit current need be considered to determine the necessary interrupting rating of a low voltage fuse.

Some system components (busway, circuit breakers, etc.), however, have a limited asymmetrical rating, therefore, both the symmetrical and the asymmetrical short-circuit currents should be calculated.

Sections 240-60 and 240-83 of the 1975 National Electrical Code cover the requirements for marking the interrupting capacity on fuses and circuit breakers. See back cover for BUSS Fuse interrupting capacities.

Section 240-60. Part (c) Marking.

Fuses shall be plainly marked, either by printing on the fuse barrel or by a label attached to the barrel, showing the following: . . . (3) interrupting rating where other than 10,000 amperes, . . .

Section 240-83. Marking. Part (C) Interrupting Rating.

Every circuit breaker having an interrupting rating other than 5000 amperes shall have its interrupting rating shown on the circuit breaker.

To be able to determine the fault current at any point in the system, we need to first draw a one-line diagram showing all of the sources of short-circuit current feeding into the fault, as well as the impedances furnished by the circuit components.

The impedances may be represented by ohms, percent ohms or per-unit ohms. The ohmic method and then the per-unit method is used in the study of three phase faults and single phase faults on typical distribution systems. An arbitrary kva base and the system voltage are selected as base values for the per-unit method.

To make the study, the system components, including those of the utility system, are represented as impedances in the diagram.

SHORT-CIRCUIT CURRENT CALCULATIONS

Consider the following system, supplied by a 1000 KVA, three phase transformer having a full load current of 2400 amperes at 240 volts. (See System-A, next page.)

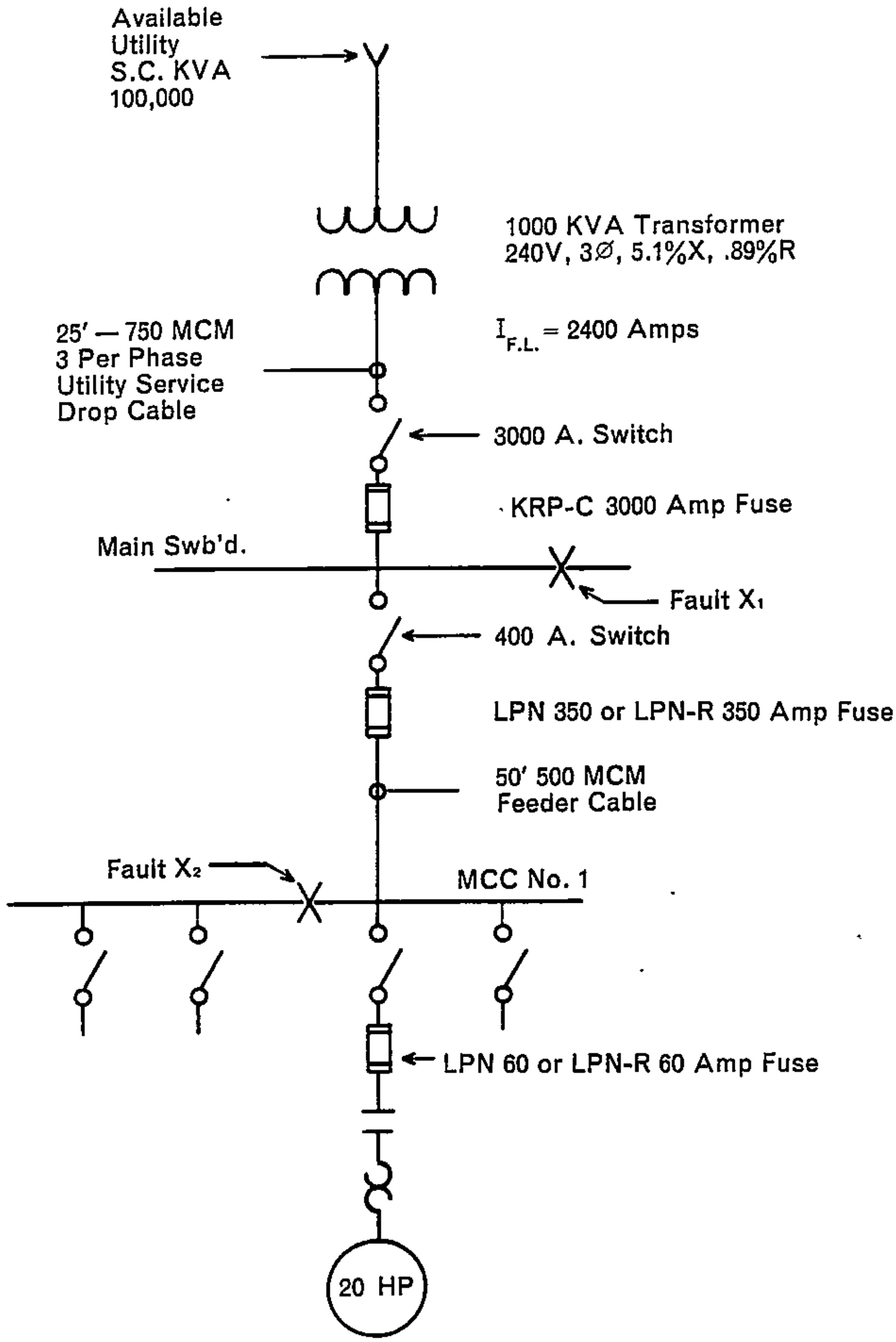
To start, we must obtain the available short-circuit KVA from the local utility company.

The utility estimates that their system can deliver a short-circuit of 100,000 KVA (100 MVA) at the transformer. Since the X/R ratio of the utility system is usually quite high, only the reactance need be considered.

With this available short-circuit fault information, we can begin to make the necessary calculations to determine the fault current at any point in the electrical system.

We can use an ohmic method, a per-unit method, or a percent method for calculating short-circuit current. In this text we will examine the ohmic and per-unit methods. The first method presented is the ohmic method.

SYSTEM A



Note: The above 1000 KVA transformer serves 100% motor load.

3 Ø SHORT-CIRCUIT CALCULATION
OHMIC METHOD PROCEDURE

Most circuit component impedances are given in ohms except utility and transformer impedances which are found by the following formulae*: (Note that the transformer and utility ohms are referred to the secondary KV by squaring the secondary voltage.)

Step 1.

$$\text{Utility } X^{\dagger} \text{(in ohms)} = \frac{1000\,(\text{secondary KV})^2}{(\text{Utility S.C. KVA})}$$

Step 2.

$$\text{Transformer X (in ohms)} = \frac{(10)(\%X)(\text{secondary KV})^2}{\text{Transformer KVA}}$$

$$\text{Transformer R (in ohms)} = \frac{(10)(\%R)(\text{secondary KV})^2}{\text{Transformer KVA}}$$

Step 3. The impedance (in ohms) given for current transformers, large switches and large circuit breakers is essentially all X.

Step 4. Cable and bus X (in ohms).
Cable and bus R (in ohms).

Step 5. Total all X and all R in system to point of fault.

Step 6. Determine impedance (in ohms) of the system by:

$$Z_T = \sqrt{(R_T)^2 + (X_T)^2}$$

Step 7. Calculate short-circuit symmetrical rms amperes at the point of fault.

$$I_{\text{s.c. rms sym}} = \frac{(\text{Secondary Line Voltage})}{\sqrt{3}\,(Z_T)}$$

*For simplicity of calculations all ohmic values are single phase distance one way, later compensated for in the three phase short- circuit formula by the factor, $\sqrt{3}$. (See Step 7.)

†Only X is considered in this procedure since utility X/R ratios are usually quite high. For more finite details obtain R of utility source.

Step 8. Determine the motor load. Add up the full load motor currents. The full load motor current in the system is generally a percentage of the transformer full load current, depending upon the type of load. (The generally accepted procedure assumes 50% motor load when both motor and lighting loads are considered, such as supplied by 4 wire, 120/208 and 277/480 volt 3-phase systems.)

Step 9. The short-circuit current that the motor load can contribute is an asymmetrical current usually approximated as being equal to the locked rotor current of the motors.* As a close approximation with a margin of safety use:

Asym Motor Contribution* = 5 x (Full load motor current)

Step 10. The symmetrical motor contribution can be approximated by using the average asymmetry factor associated with the motors in the system. This asymmetry factor varies according to motor design and in this text may be chosen as 1.25 for approximate calculation purposes. To solve for the symmetrical motor contribution:

$$\text{Sym Motor Contribution*} = \frac{\text{(Asym Motor Contribution)}}{1.25}$$

Step 11. The total symmetrical short-circuit rms current is calculated as:

† Total $I_{s.c.\ rms\ sym} = (I_{s.c.\ rms\ sym}) + \text{(Sym Motor Contribution)}$

Step 12. Determine X/R ratio of the system to the point of fault.

$$\text{X/R ratio} = \frac{\text{Total X (Ohms)}}{\text{Total R (Ohms)}}$$

Step 13. The asymmetrical factor corresponding to the X/R ratio in Step 12 is found in Table 8, Column M_m. This multiplier will provide the worst case asymmetry occuring in the first ½ cycle. Where the average 3-phase multiplier is desired use column M_a.

Step 14. Calculate the asymmetrical rms short-circuit current.

$I_{s.c.\ asym\ rms} = (I_{s.c.\ rms\ sym}) \times \text{(Asymmetrical Factor)}$

Step 15. The total asymmetrical short-circuit rms current is calculated as:

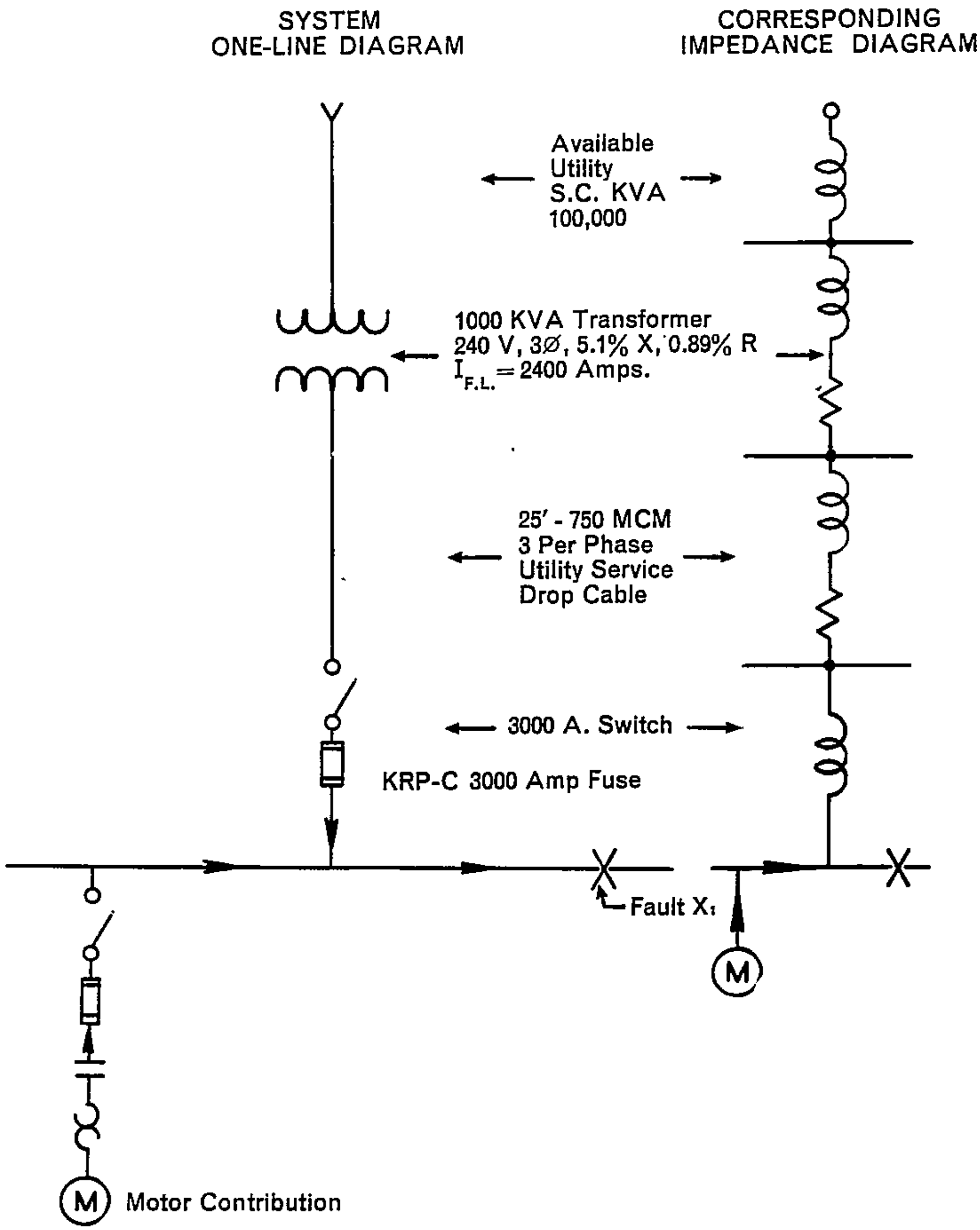
† Total $I_{s.c.\ asym\ rms} = (I_{s.c.\ asym\ rms}) + \text{(Asym Motor Contribution)}$

*A more exact determination depends upon the sub-transient reactances of the motors in question and associated circuit impedances. A less conservative method would involve the total motor circuit impedance to a common bus (sometimes referred to as a "zero reactance bus") and proceed there-from.

†Arithmetical addition results in conservative values of fault current. More finite values involve vectoral addition of the currents.

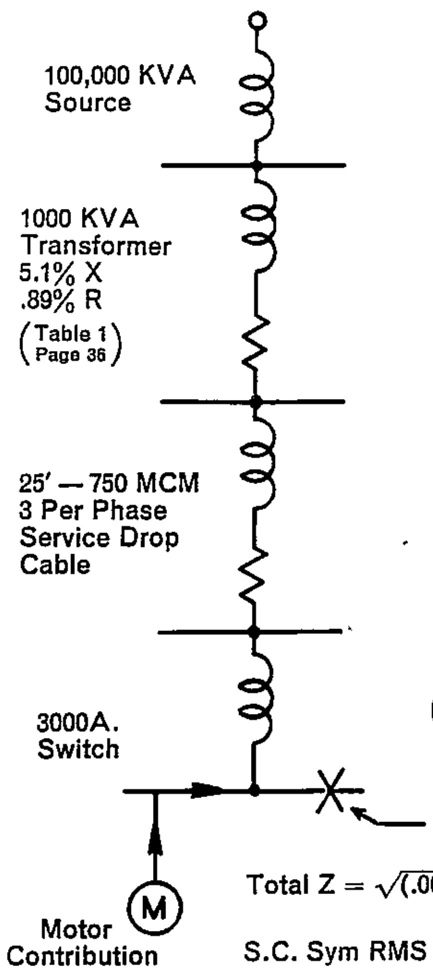
NOTE: All of the ohms of the circuit components must be referred to the same voltage. If there is more than one voltage transformation in the system, the ohmic method becomes more complicated. It is recommended that the per-unit method be used for ease in calculation when more than one voltage transformation exists in the system. See page 23.

OHMIC METHOD
ONE-LINE DIAGRAM TO FAULT X_1 — SYSTEM-A



OHMIC METHOD
3 Ø SHORT-CIRCUIT CALCULATION — FAULT X_1

IMPEDANCE DIAGRAM



$$X = \frac{1000\ (.240)^2}{100{,}000} = .000575$$

$$X = \frac{(10)\ (5.1)\ (.240)^2}{1000} = .002940$$

$$R = \frac{10\ (.89)\ (.240)^2}{1000} = .000512$$

(Table 5, Page 38) $X = \frac{25'}{1000'} \times \frac{.0356}{3} = .000300$

(Table 5, Page 38) $R = \frac{25'}{1000'} \times \frac{.0194}{3} = .000162$

(Table 3, Page 37) $X = .000040$

	R	X
		.000575
		.002940
	.000512	
		.000300
	.000162	
		.000040
Total R and Total X =	.000674	.003855

Total $Z = \sqrt{(.000674)^2 + (.003855)^2} = .00392$ Ohms Per Phase

S.C. Sym RMS Amps $= \frac{240}{\sqrt{3}\ (.00392)} = 35{,}300$ Amps.

Asym Motor Contribution (100% Motor Load) = 5 x 2400 = 12,000 Amps.

Sym Motor Contribution $= \frac{12{,}000}{1.25} = 9600$ Amps.

Total S.C. Sym RMS Amps (Fault X_1) = 35,300 + 9,600 = 44,900 Amps.

X/R Ratio $= \frac{.003855}{.000674} = 5.72$

Asym Factor* = 1.290 (Table 8, Page 40)

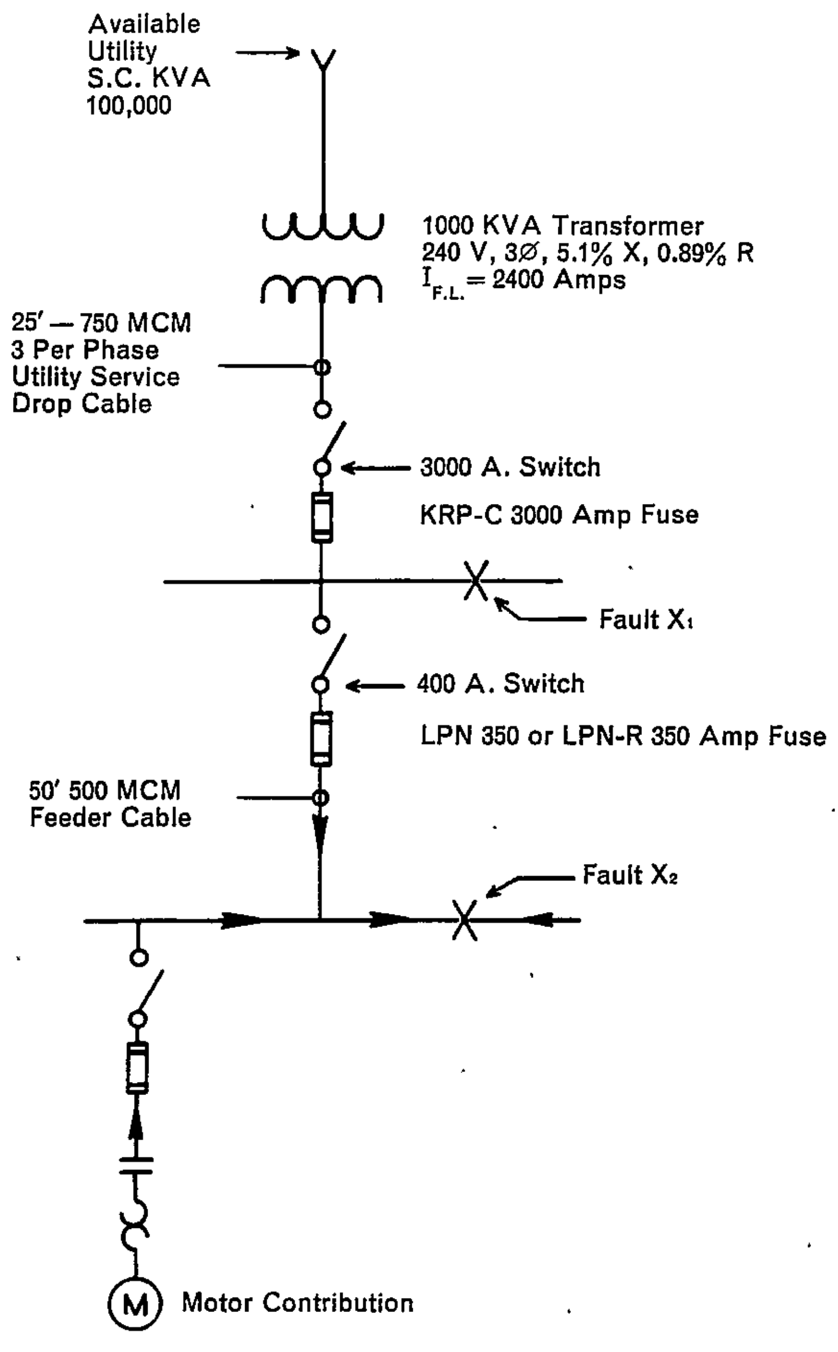
S.C. Asym RMS Amps = 1.290 x 35,300 = 45,500 Amps.

Total S.C. Asym RMS Amps (Fault X_1) = 45,500 + 12,000 = 57,500 Amps.

NOTE: See Ohmic Method Procedure for Formulas.

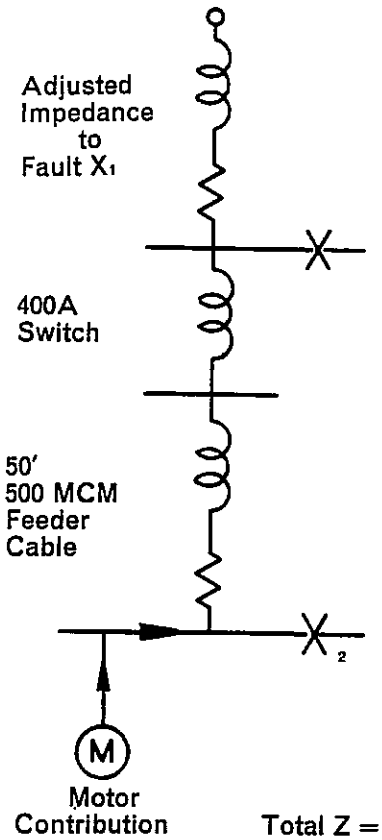
*Multiplier for maximum one-phase rms amperes at ½ cycle.

OHMIC METHOD — Con't.
ONE-LINE DIAGRAM TO FAULT X_2 — SYSTEM-A



OHMIC METHOD — Con't.
3 ∅ SHORT-CIRCUIT CALCULATION — FAULT X_2

IMPEDANCE DIAGRAM



	R	X
X = .003855		.003855
R = .000674	.000674	
(Table 3, Page 37) X = .00008		.000080
(Table 5, Page 38) $X = \frac{50'}{1000'} \times .0466 = .00233$		.002330
(Table 5, Page 38) $R = \frac{50'}{1000'} \times .0294 = .00147$	.001470	
Total R and Total X =	.002144	.006265

$$\text{Total } Z = \sqrt{(.002144)^2 + (.006265)^2} = .00662 \text{ Ohms Per Phase}$$

$$\text{S.C. Sym RMS Amps} = \frac{240}{\sqrt{3}\,(.00662)} = 20{,}930 \text{ Amps.}$$

Asym Motor Contribution (100%) = 5 x 2400 = 12,000 Amps.†

$$\text{Sym Motor Contribution} = \frac{12{,}000}{1.25} = 9600 \text{ Amps.}†$$

Total S.C. Sym RMS Amps (Fault X_2) = 20,930 + 9600 = 30,530 Amps.

$$X/R \text{ Ratio} = \frac{.006265}{.002144} = 2.92$$

Asym Factor* = 1.112 (Table 8, Page 41)

S.C. Asym RMS Amps = 1.112 x 20,930 = 23,310 Amps.

Total S.C. Asym RMS Amps (Fault X_2) = 23,310 + 12,000 = 35,310 Amps.

NOTE: See Ohmic Method Procedure for Formulas.

†Actual motor contribution will be somewhat smaller than calculated due to the impedance of the feeder cable.

*Multiplier for maximum one-phase rms amperes at ½ cycle.

3 Ø SHORT-CIRCUIT CALCULATION PER-UNIT METHOD PROCEDURE*

The per-unit method is generally used for calculating short-circuit currents where the electrical system is more complex than our simple example.

After establishing a one-line diagram of the system, we proceed to the following calculations:**

Step 1. Utility per-unit X† $= \dfrac{\text{Base KVA}}{\text{Utility S.C. KVA}}$

Step 2. Transformer per-unit X $= \dfrac{(\%X)\ (\text{Base KVA})}{(100)\ (\text{Transformer KVA})}$

Transformer per-unit R $= \dfrac{(\%R)\ (\text{Base KVA})}{(100)\ (\text{Transformer KVA})}$

Step 3. Component per-unit X $= \dfrac{(\text{Ohm X})\ (\text{Base KVA})}{(1000)\ (\text{KV})^2}$
(Cable, Switches, CT, Bus)

Step 4. Component per-unit R $= \dfrac{(\text{Ohm R})\ (\text{Base KVA})}{(1000)\ (\text{KV})^2}$
(Cable, Switches, CT, Bus)

Step 5. Next, total all per-unit X and all per-unit R in system to point of fault.

Step 6. Determine the per-unit impedance of the system by:

Per-Unit $Z_T = \sqrt{(P.U.R_T)^2 + (P.U.X_T)^2}$

Step 7. Calculate the symmetrical rms short-circuit current at the point of fault.

$$I_{\text{s.c. rms sym}} = \frac{\text{Base KVA}}{\sqrt{3} \times KV \times (P.U.Z_T)}$$

*The base KVA used throughout this text will be 10,000 KVA.

**As in the ohmic method procedure, all ohmic values are single-phase distance one way, later compensated for in the three phase short-circuit formula by the factor, $\sqrt{3}$. (See Step 7.)

†Only per-unit X is considered in this procedure since utility X/R ratio is usually quite high. For more finite details obtain per-unit R of utility source.

Step 8. Determine the motor load. Add up the full load motor currents. (Whenever motor and lighting loads are considered, such as supplied by 4 wire, 120/208 and 277/480 volt 3 phase systems, the generally accepted procedure is to assume 50% motor load based on the full load current rating of the transformer.)

Step 9. The short-circuit current that the motor load can contribute is an asymmetrical current usually approximated as being equal to the locked rotor current of the motors.* As a close approximation with a margin of safety use:

$$\text{Asym Motor Contribution}^{*} = 5 \times (\text{Full load motor current})$$

Step 10. The symmetrical motor contribution can be approximated by using the average asymmetry factor associated with the motors in the system. This asymmetry factor varies according to motor design and in this text may be chosen as 1.25 for approximate calculation purposes. To solve for the symmetrical motor contribution:

$$\text{Sym Motor Contribution}^{*} = \frac{(\text{Asym Motor Contribution})}{1.25}$$

Step 11. The total symmetrical short-circuit rms current is calculated as :

$$\dagger\ \text{Total } I_{\text{s.c. rms sym}} = (I_{\text{s.c. rms sym}}) + (\text{Sym Motor Contribution})$$

Step 12. Determine X/R ratio of the system to the point of fault.

$$\text{X/R ratio} = \frac{\text{P.U.}X_T}{\text{P.U.}R_T}$$

Step 13. From Table (8), Column M_m, obtain the asymmetrical factor corresponding to the X/R ratio determined in Step 12. This multiplier will provide the worst case asymmetry occurring in the first ½ cycle. Where the average 3-phase multiplier is desired use column M_a.

Step 14. The asymmetrical rms short-circuit current can be calculated as:

$$I_{\text{s.c. asym rms}} = (I_{\text{s.c. rms sym}}) \times (\text{Asymmetrical Factor})$$

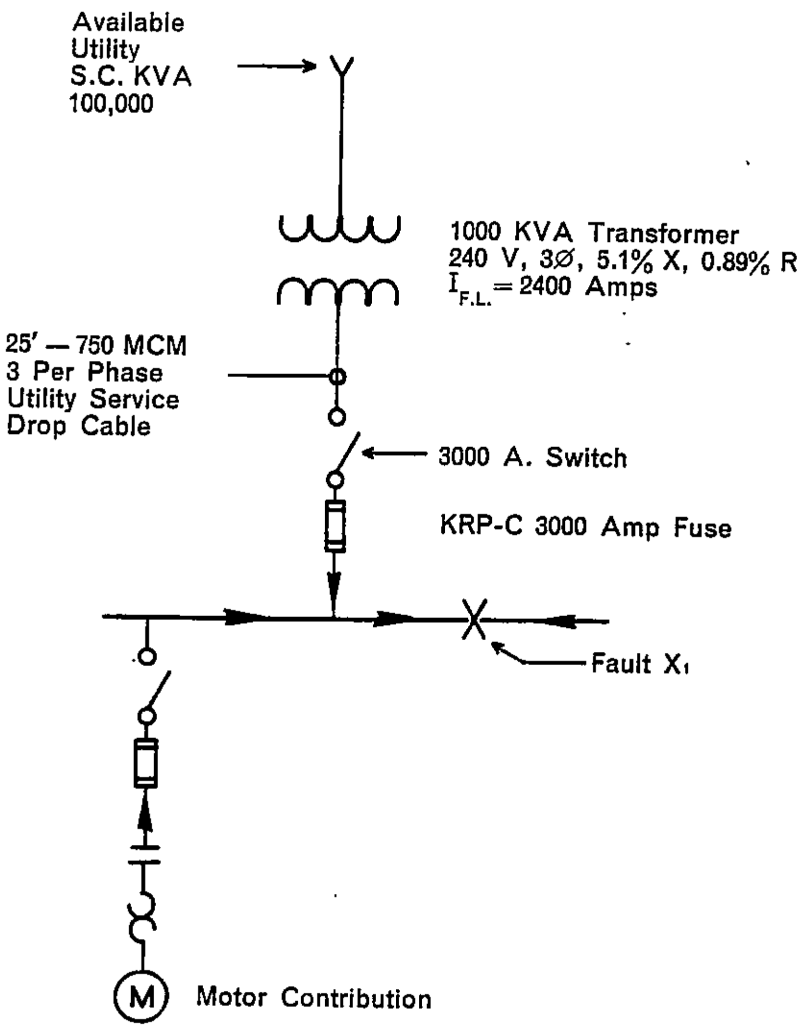
Step 15. The total asymmetrical short-circuit rms current is calculated as:

$$\dagger\ \text{Total } I_{\text{s.c. asym rms}} = (I_{\text{s.c. asym rms}}) + (\text{Asym Motor Contribution})$$

*A more exact determination depends upon the sub-transient reactances of the motors in question and associated circuit impedances. A less conservative method would involve the total motor circuit impedance to a common bus (sometimes referred to as a "zero reactance bus") and proceed there-from.

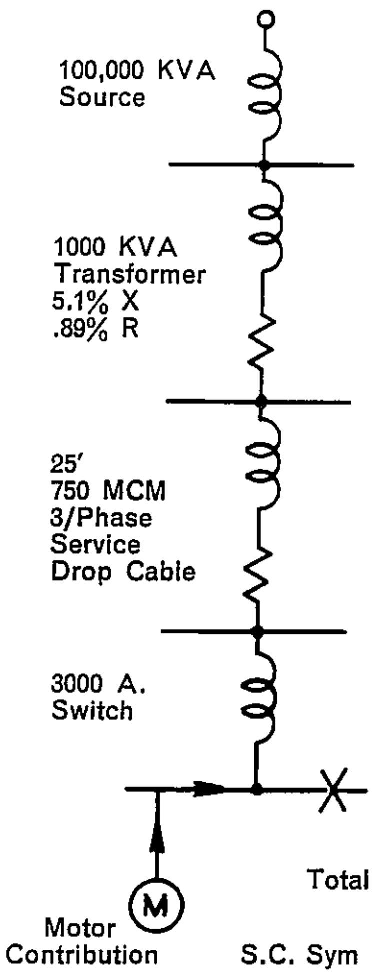
†Arithmetical addition results in conservative values of fault current. More finite values involve vectoral addition of the currents.

PER UNIT METHOD
ONE-LINE DIAGRAM TO FAULT X1 — SYSTEM-A



PER UNIT METHOD
3 Ø SHORT-CIRCUIT CALCULATION — FAULT X_1

IMPEDANCE DIAGRAM



$$P.U.X = \frac{10{,}000}{100{,}000} = .1000$$

$$P.U.X = \frac{(5.1)\ (10{,}000)}{(100)\ (1000)} = .5100$$

$$P.U.R = \frac{(.89)\ (10{,}000)}{(100)\ (1000)} = .0890$$

$$P.U.X = \frac{(.0003)^{\dagger}(10{,}000)}{(1000)\ (.240)^2} = .0520$$

$$P.U.R = \frac{(.00016)^{\dagger}(10{,}000)}{(1000)\ (.240)^2} = .0281$$

$$P.U.X = \frac{(.00004)\ (10{,}000)}{(1000)\ (.240)^2} = .0069$$

10,000 KVA Base

P.U.R.	P.U.X
	.1000
	.5100
.0890	
	.0520
.0281	
	.0069
.1171	.6689

Total P.U.R and P.U.X = .1171, .6689

$$\text{Total P.U.Z} = \sqrt{(.1171)^2 + (.6689)^2} = .6800$$

$$\text{S.C. Sym RMS Amps} = \frac{10{,}000}{(\sqrt{3})\ (.240)\ (.68)} = 35{,}300 \text{ Amps.}$$

Asym Motor Contribution (100%) = 5 x 2400 = 12,000 Amps.

$$\text{Sym Motor Contribution} = \frac{12{,}000}{1.25} = 9600 \text{ Amps.}$$

Total S.C. Sym RMS Amps (Fault X_1) = 35,300 + 9,600 = 44,900 Amps.

$$\text{X/R Ratio} = \frac{.6689}{.1171} = 5.72, \text{ Asym Factor*} = 1.290$$

S.C. Asym RMS Amps = 1.290 x 35,300 = 45,500 Amps.

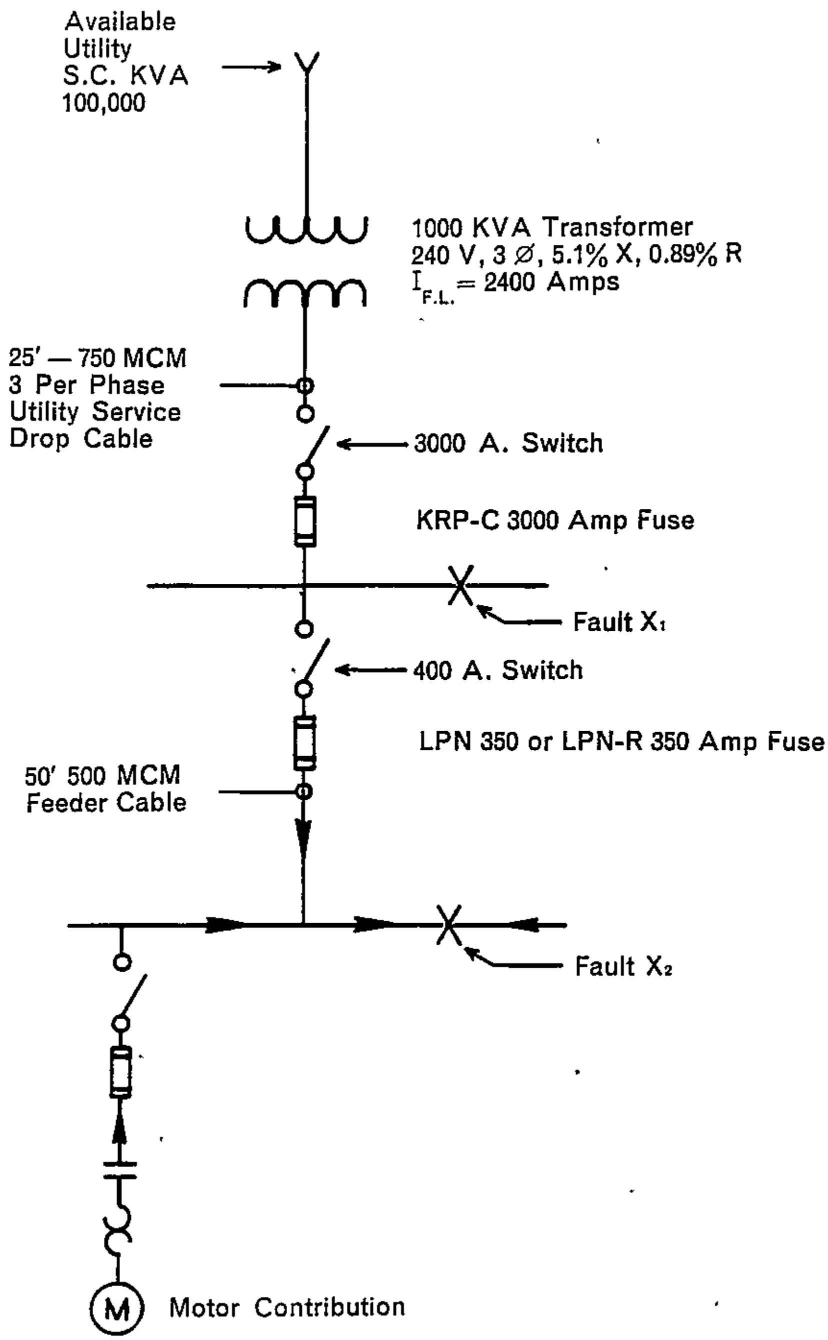
Total S.C. Asym RMS Amps (Fault X_1) = 45,500 + 12,000 = 57,500 Amps.

NOTE: See Per Unit Method Procedure for Formulas.

†See Page 9 for determination of these values.

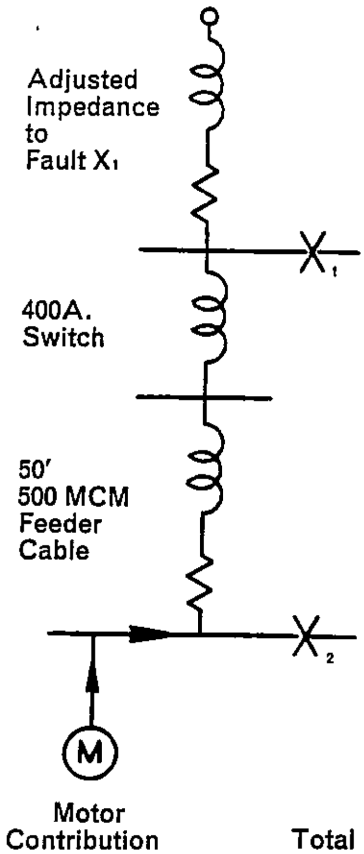
*Multiplier for maximum one-phase rms amperes at ½ cycle.

PER UNIT METHOD (Con't.)
ONE-LINE DIAGRAM TO FAULT X_2 — SYSTEM-A



PER UNIT METHOD (Con't.)
3 ∅ SHORT-CIRCUIT CALCULATION — FAULT X_2

IMPEDANCE DIAGRAM



$$P.U.X = .6689$$

$$P.U.R = .1171$$

$$P.U.X = \frac{(.00008)\ (10{,}000)}{(1000)\ (.240)^2} = .0139$$

$$P.U.X = \frac{(.00233)^{\dagger}(10{,}000)}{(1000)\ (.240)^2} = .4050$$

$$P.U.R = \frac{(.00147)^{\dagger}(10{,}000)}{(1000)\ (.240)^2} = .2551$$

10,000 KVA BASE

P.U.R.	P.U.X.
	.6689
.1171	
	.0139
	.4050
.2551	
.3722	1.0878

Total P.U.R and P.U.X = .3722, 1.0878

$$\text{Total P.U.Z.} = \sqrt{(.3722)^2 + (1.0878)^2} = 1.150$$

$$\text{S.C. Sym RMS Amps} = \frac{10{,}000}{(\sqrt{3})\ (.240)\ (1.15)} = 20{,}930 \text{ Amps.}$$

Asym Motor Contribution (100%) = 5 x 2400 = 12,000 Amps.††

$$\text{Sym Motor Contribution} = \frac{12{,}000}{1.25} = 9600 \text{ Amps.}^{\dagger\dagger}$$

Total S.C. Sym RMS.Amps (Fault X_2) = 20,930 + 9600 = 30,530 Amps.

$$X/R \text{ Ratio} = \frac{1.0878}{.3722} = 2.92, \text{ Asym Factor*} = 1.112$$

S.C. Asym RMS Amps = 1.112 x 20,930 = 23,310 Amps.

Total S.C. Asym RMS Amps (Fault X_2) = 23,310 + 12,000 = 35,310 Amps.

NOTE: See Per Unit Method Procedure for Formulas.

†See Page 11 for determination of these values.

††Actual motor contribution will be somewhat smaller than calculated due to impedance of the feeder cable.

*Multiplier for maximum one-phase rms amperes at ½ cycle.

PER-UNIT METHOD PROCEDURE MADE SIMPLE
—USE OF CONSTANTS—

The per-unit method lends itself rather well to the use of constants based on a base KVA (10,000) and a base voltage. The following tables* are convenient when used in conjunction with per-unit short-circuit calculations:

INDEX TO TABLES—USE OF CONSTANTS

***Note:** These tables are derived using a base KVA of 10,000.

Table A—UTILITY SHORT-CIRCUIT KVA—P.U.X.

$$P.U.X = \frac{\text{Base KVA}}{\text{Utility S.C. KVA}}$$

Utility Short-Circuit KVA	P.U.X
25,000	0.400
50,000	0.200
75,000	0.133
100,000	0.100
200,000	0.050
300,000	0.033
400,000	0.025
500,000	0.020
1,000,000	0.010
Infinite	0

Table B—TRANSFORMER IMPEDANCE MULTIPLIERS

$$P.U.X = \frac{(\%X)\ (\text{Base KVA})}{(100)\ (\text{Transformer KVA})}$$

Transformer KVA	Multiplier
50	2.0000
75	1.3333
100	1.0000
150	.6667
167	.5988
200	.5000
225	.4444
300	.3333
500	.2000
750	.1333
1000	.1000
1500	.0667
2000	.0500
2500	.0400

Example: 750 KVA Transformer, 5% X, 1% R

P.U.X. = 5 x .1333 = .6665

P.U.R. = 1 x .1333 = .1333

Table C — COMPONENT IMPEDANCE MULTIPLIERS

System Voltage	Multiplier
120	694.44
208	231.14
220	206.50
240	173.61
416	57.78
440	51.60
460	47.26
480	43.40
550	33.10
600	27.78
2400	1.736
4160	.579
12.47 KV	.0649
13.2 KV	.0574
13.8 KV	.0525

(Based on System Voltage)

$$P.U.X = \frac{(\text{Ohms X})\ (\text{Base KVA})}{(1000)\ (\text{KV})^2}$$

Examples:

No. 1 — 1000 Feet 500 MCM Cable, R = .0294 ohm
X = .0466 ohm, 480 volt system
P.U.X = .0466 x 43.4 = 2.060
P.U.R = .0294 x 43.4 = 1.277

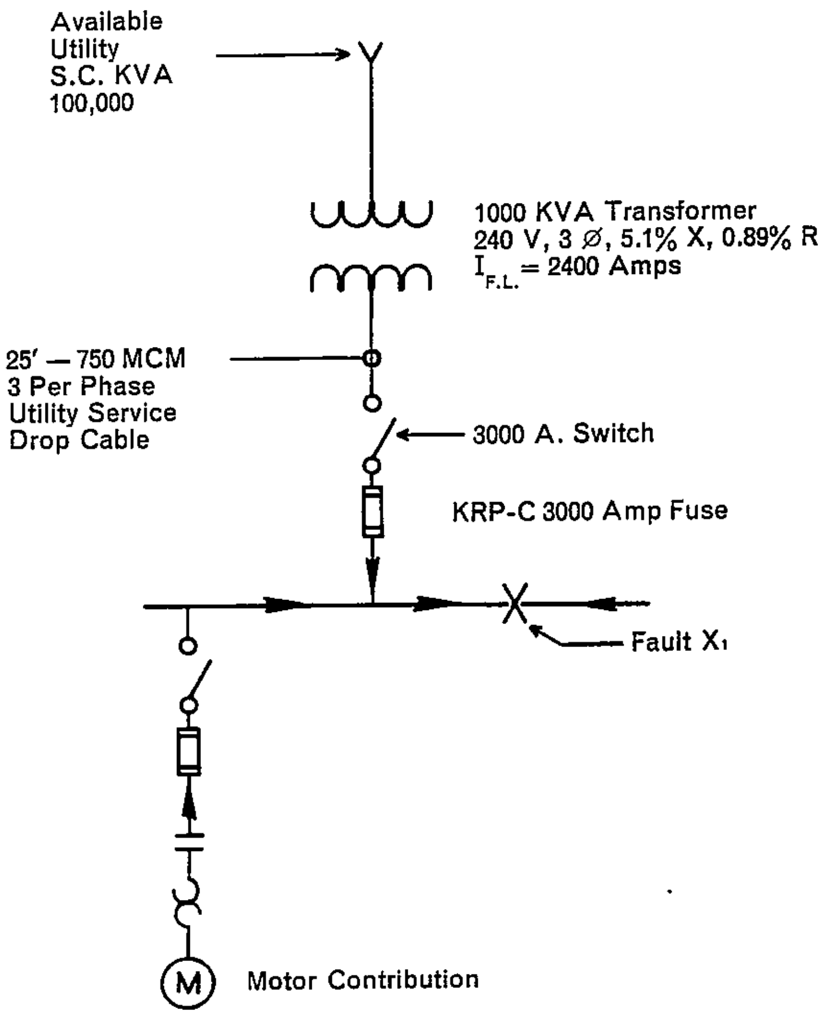
No. 2 — 1800 Amp Current Transformer,
X = .00007 ohms, 208 volt system
P.U.X = .00007 x 231.14 = .0162

Table D — SYMMETRICAL RMS SHORT-CIRCUIT CURRENT FORMULAS
(BASED ON SYSTEM VOLTAGE AND 10,000 KVA BASE)

Three Phase Formula	Three Phase System Voltage Line-Line Volts	Symmetrical RMS Short-Circuit Current Equals
$I_{S.C.A.} = \frac{\text{KVA Base}}{\sqrt{3} \times \text{KV} \times \text{Total P.U.Z}}$	208	27,758/Total P.U.Z
	220	26,280/Total P.U.Z
	240	24,039/Total P.U.Z
	416	13,895/Total P.U.Z
	440	13,120/Total P.U.Z
Three Phase Example:	460	12,551/Total P.U.Z
	480	12,019/Total P.U.Z
Total P.U.Z to fault is 0.825 and system voltage is 240 volts. Find symmetrical rms short-circuit current.	550	10,500/Total P.U.Z
	600	9,634/Total P.U.Z
	2400	2,406/Total P.U.Z
	4160	1,389/Total P.U.Z
$I_{S.C.A.} = \frac{24,039}{0.825} = 29,180$ rms amps	12.47 KV	463/Total P.U.Z
	13.2 KV	438/Total P.U.Z
	13.8 KV	419/Total P.U.Z

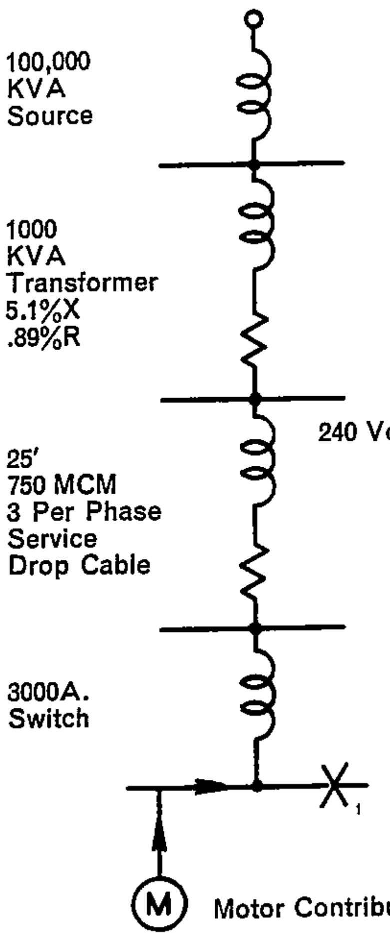
Single Phase Formula	Single Phase System Voltage	Symmetrical RMS Short-Circuit Current Equals
$I_{S.C.A.} = \frac{\text{KVA Base}}{\text{KV} \times \text{P.U.Z}}$	120	83333 /Total P.U.Z
	220	45455 /Total P.U.Z
	240	41667 /Total P.U.Z
	480	20833 /Total P.U.Z

PER UNIT METHOD—USE OF CONSTANTS
ONE-LINE DIAGRAM TO FAULT X_1—SYSTEM-A



PER UNIT METHOD—USE OF CONSTANTS
3 ∅ SHORT-CIRCUIT CALCULATION—FAULT X_1

IMPEDANCE DIAGRAM



P.U.X = .1000 (Table A Page 19)

P.U.X = (5.1) x (.1000) = .5100 (Table B Page 19)

P.U.R = (.89) x (.1000) = .0890 (Table B Page 19)

P.U.X. = (.0003)† x (173.61) = .0520 (Table C Page 20)

P.U.R = (.00016)† x (173.61) = .0281 (Table C Page 20)

P.U.X = (.00004) x (173.61) = .0069 (Table C Page 20)

10,000 KVA BASE

P.U.R	P.U.X
	.1000
	.5100
.0890	
	.0520
.0281	
	.0069
.1171	.6689

Total P.U.R and P.U.X = .1171, .6689

Total P.U.Z = .6800

Short-Circuit Symmetrical RMS Amps (Table D Page 20) $= \frac{24{,}039}{.6800} =$ 35,300 Amps.

Asym Motor Contribution (100%) = 5 x 2400 = 12,000 Amps.

Sym Motor Contribution $= \frac{12{,}000}{1.25} =$ 9600 Amps.

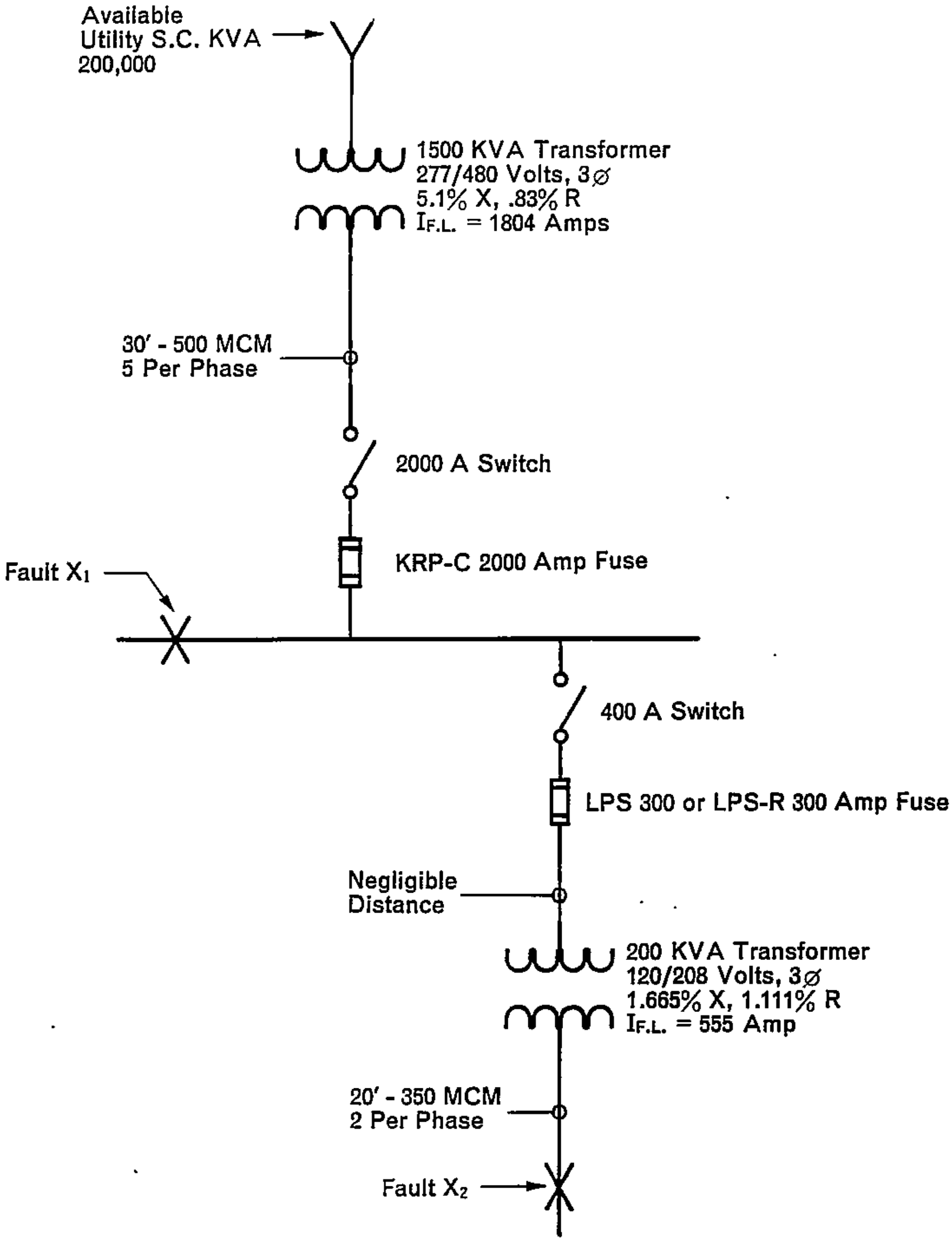
Total Short-Circuit Symmetrical RMS Amps (Fault X_1) = 35,300 + 9600 = 44,900 Amps.

NOTE: Proceed as before for asymmetrical current.

†See Page 9 for determination of these values.

DOUBLE TRANSFORMATION
PER-UNIT METHOD
ONE-LINE DIAGRAM TO FAULT X_1 & X_2

The per-unit method simplifies the short-circuit current calculations when there is more than one voltage transformation. The following example illustrates the relative ease in calculating the 3-ø fault current at X_2:

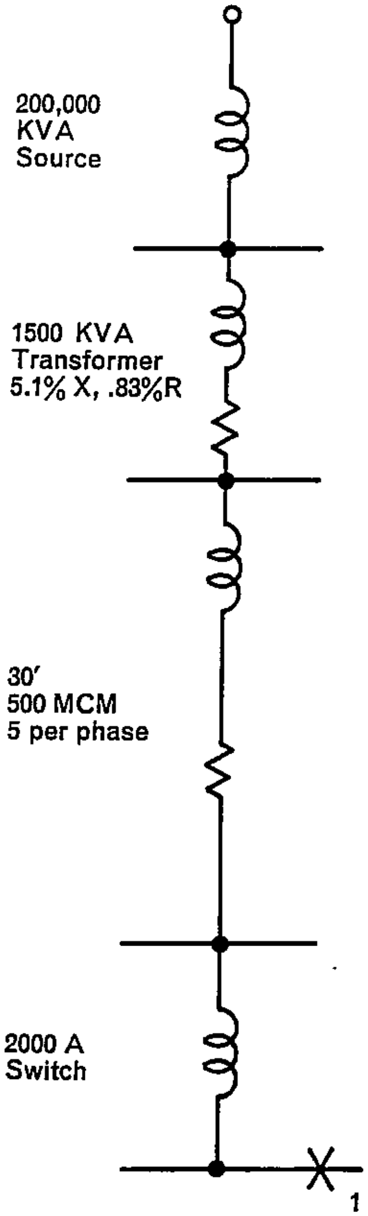


Note: In this example, motor contribution is not included. See page 13 for motor contribution procedure.

DOUBLE TRANSFORMATION
PER-UNIT METHOD
3 ϕ SHORT-CIRCUIT CALCULATIONS — FAULT X_1

Fault X_1 is located on the 277/480 volt system; therefore, the base voltage for the calculations is 480 volts.

IMPEDANCE DIAGRAM



$$P.U.X = \frac{10,000}{200,000} = .05$$

$$P.U.X = \frac{(5.1)\ (10,000)}{(100)\ (1500)} = 5.1 \text{ X } .0667 =$$

$$P.U.R = \frac{(.83)\ (10,000)}{(100)\ (1500)} = .83 \text{ X } .0667 =$$

$$P.U.X = \left[\left(\frac{30'}{1000'}\right)\left(\frac{.0466}{5}\right)\right] \text{X} \frac{10,000}{(1000)\ (.480)^2}$$

$$= .00028 \text{ X } 43.4 =$$

$$P.U.R = \left[\left(\frac{30'}{1000'}\right)\left(\frac{.0294}{5}\right)\right] \text{X} \frac{10,000}{(1000)\ (.480)^2}$$

$$= .00018 \text{ X } 43.4 =$$

$$P.U.X = (.00005) \frac{10,000}{1000\ (.480)^2}$$

$$= .00005 \text{ X } 43.4 =$$

Total P.U.R & P.U.X =

10,000 KVA Base

P.U.R	P.U.X
	.0500
	.3402
.0554	
	.0121
.0077	
	.0022
.0631	.4045

$$\text{Total P.U.Z} = \sqrt{(.0631)^2 + (.4045)^2} = .4094$$

$$\underline{\text{S.C. Sym RMS Amps (Fault } X_1)} = \frac{10,000}{\sqrt{3}(.480)\ (.4094)} = \frac{12,019}{.4094} = \underline{29,360 \text{ Amps}}$$

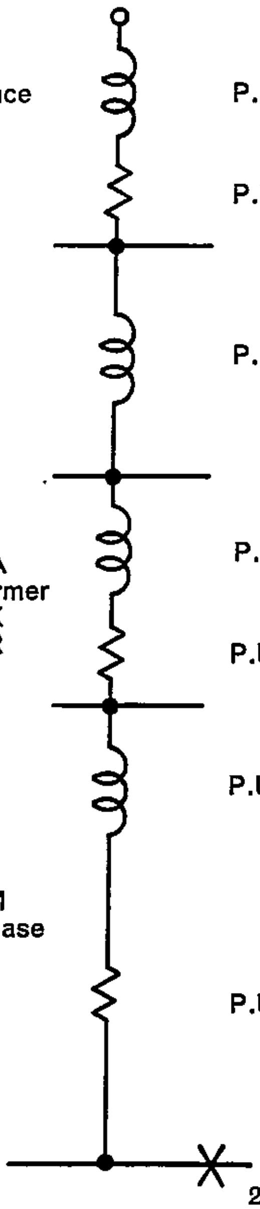
Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

DOUBLE TRANSFORMATION
PER UNIT METHOD
3 ∅ SHORT-CIRCUIT CALCULATIONS – FAULT X_2

Fault X_2 is located on the 120/208 volt system. The per-unit method makes the calculations simple. The base voltage is 208 volts for the system components on the 120/208 volt system. These P.U. impedance values can be added directly to the P.U. impedance values determined on the 480 volt system using the 480 volt base.

If the ohmic method were to be used, the calculations would be considerably more complex. To find Fault X_2, the system ohms to the primary of the 200 KVA transformer would have to be adjusted by the square of the turns ratio. However, the per-unit method automatically accounts for this adjustment. In the calculations which follow, particular attention should be given to the voltage in the per-unit multipliers.

IMPEDANCE DIAGRAM



10,000 KVA Base

		P.U.R	P.U.X
Impedance To Fault X_1	$P.U.X = .4045$		.4045
	$P.U.R = .0631$	.0631	
400 A Switch	$P.U.X = (.00008)\frac{10,000}{1000\,(.480)^2} = .00008 \times 43.4 =$		.0035
200 KVA Transformer 1.665% X 1.111% R	$P.U.X = \frac{(1.665)\,(10,000)}{(100)\,(200)} = 1.665 \times .5 =$		.8325
	$P.U.R = \frac{(1.111)\,(10,000)}{(100)\,(200)} = 1.111 \times .5 =$	.5555	
20′ 350 MCM 2 Per Phase	$P.U.X = \left[\left(\frac{20'}{1000'}\right)\left(\frac{.0491}{2}\right)\right] \times \frac{10,000}{(1000)\,(.208)^2} = .000491 \times 231.14 =$		.1135
	$P.U.R = \left[\left(\frac{20'}{1000'}\right)\left(\frac{.0378}{2}\right)\right] \times \frac{10,000}{(1000)\,(.208)^2} = .00038 \times 231.14 =$	.0874	
	Total P.U.R & P.U.X =	.7060	1.3540

$$\text{Total P.U.Z} = \sqrt{(.706)^2 + (1.354)^2} = 1.5270$$

$$\underline{\text{S.C. Sym RMS Amps (Fault } X_2)} = \frac{10,000}{\sqrt{3}(.208)\,(1.5270)} = \frac{27,758}{1.5270} = \underline{18,180 \text{ Amps}}$$

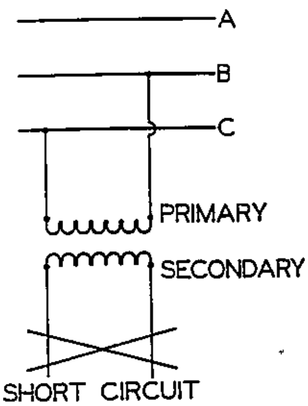
Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

1 Ø SHORT-CIRCUIT CALCULATION
ON
SINGLE-PHASE TRANSFORMER SYSTEM
PER-UNIT METHOD PROCEDURE

Short-circuit calculations on a single-phase center tapped transformer system require a slightly different procedure than 3-Ø faults on 3-Ø systems.

1. It is necessary that the proper impedance be used to represent the primary system. For 3-Ø fault calculations, a single primary conductor impedance is only considered from the source to the transformer connection. This is compensated for in the 3-Ø short-circuit formula by multiplying the single conductor or single-phase impedance by 1.73.

However, for single-phase faults, a primary conductor impedance is considered from the source to the transformer and back to the source. This is compensated in the calculations by multiplying the 3-Ø primary source impedance by two.

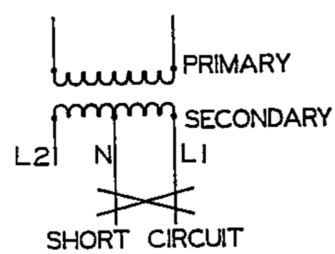


2. The impedance of the center-tapped transformer must be adjusted for the half-winding (generally line-to-neutral) fault condition.

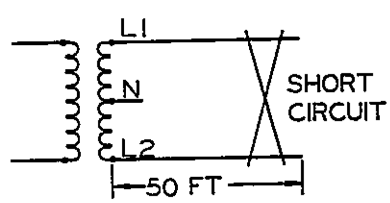
The diagram at the right illustrates that during line-to-neutral faults, the full primary winding is involved but, only the half-winding on the secondary is involved. Therefore, the actual transformer reactance and resistance of the half-winding condition is different than the actual transformer reactance and resistance of the full winding condition. Thus, adjustment to the %X and %R must be made when considering line-to-neutral faults. The adjustment multipliers generally used for this condition are as follows:

1.5 times full winding %R on full winding basis

1.2 times full winding %X on full winding basis.



3. The impedance of the cable and two-pole switches on the system must be considered "both-ways" since the current flows to the fault and then returns to the source. For instance, if a line-to-line fault occurs 50 feet from a transformer, then 100 feet of cable impedance must be included in the calculation.



The calculations on the following pages illustrate 1-Ø fault calculations on a single-phase transformer system. Both line-to-line and line-to-neutral faults are considered.

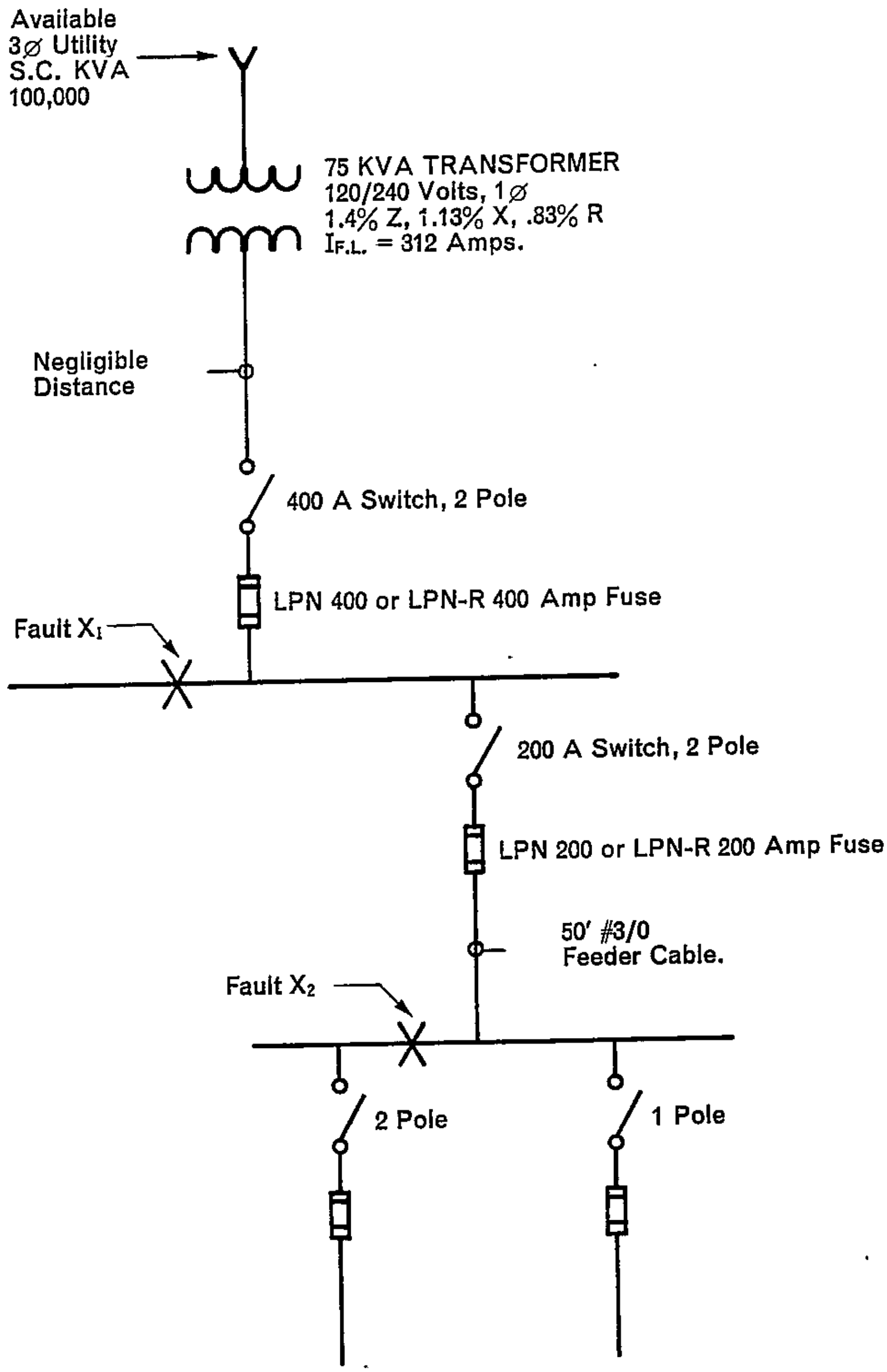
Please note in these examples:

a. The multiplier of 2 for some electrical components to account for the single-phase fault current flow,

b. The half-winding transformer %X and %R multipliers for the line-to-neutral fault situation, and

c. The KVA and voltage bases used in the per-unit calculations.

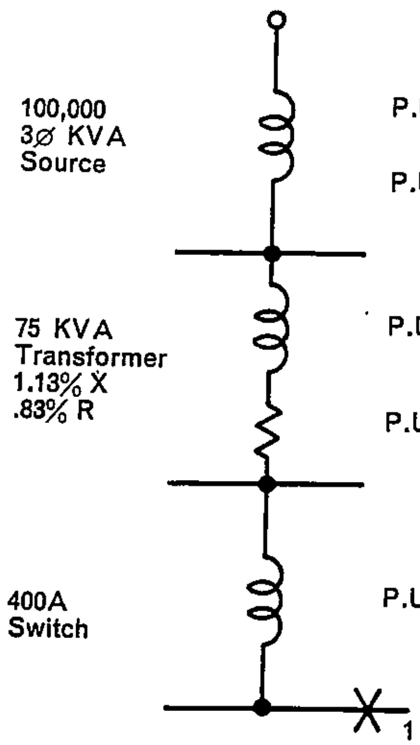
ONE LINE DIAGRAM



LINE TO LINE FAULT @ 240 VOLTS

SINGLE PHASE TRANSFORMER
PER UNIT METHOD
1 Ø SHORT-CIRCUIT CALCULATION — FAULT X_1

IMPEDANCE DIAGRAM



10,000 KVA Base

$$P.U.X\,(3\varnothing) = \frac{10{,}000}{100{,}000} = .1$$

$$P.U.X\,(1\varnothing) = 2 \times .1 = .2$$

$$P.U.X = \frac{(1.13)\,(10{,}000)}{(100)(75)} = (1.13)\,(1.33) =$$

$$P.U.R = \frac{(.83)\,(10{,}000)}{(100)(75)} = (.83)\,(1.33) =$$

$$P.U.X = \frac{2\,(.00008)\,10{,}000}{1000\,(.240)^2} = 2\,(.00008)\,(173.61) =$$

Total P.U.R & P.U.X =

	P.U.R	P.U.X
P.U.X (1Ø)		.2000
Transformer P.U.X		1.5029
Transformer P.U.R	1.1039	
Switch P.U.X		.0278
Total P.U.R & P.U.X	1.1039	1.7307

$$\text{Total P.U.Z} = \sqrt{(1.1039)^2 + (1.7307)^2} = 2.0527$$

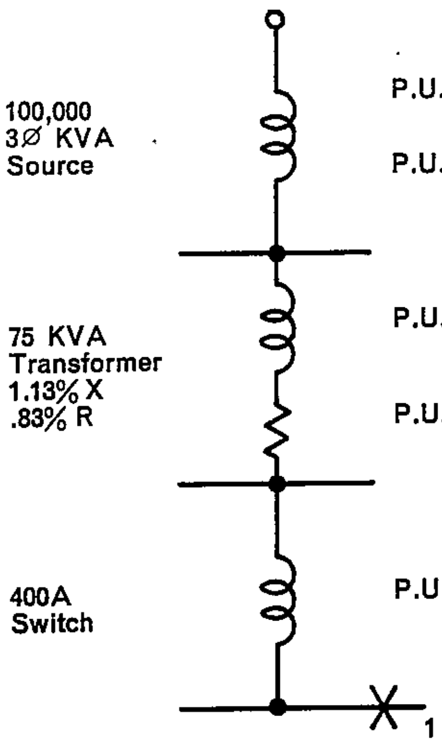
$$\underline{\text{Line to Line S.C. Sym RMS AMPS @ 240 Volts}} = \frac{10{,}000}{.240(2.0527)} = \frac{41{,}667}{(2.0527)} = \underline{20{,}300 \text{ Amps}}$$

Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

LINE TO NEUTRAL FAULT @ 120 V

SINGLE PHASE TRANSFORMER
PER UNIT METHOD
1 Ø SHORT-CIRCUIT CALCULATION — FAULT X_1

IMPEDANCE DIAGRAM



10,000 KVA Base

$$P.U.X\ (3Ø) = \frac{10,000}{100,000} = .1$$

$$P.U.X\ (1Ø) = 2 \times .1 = .2000$$

$$P.U.X = (1.2) \times \frac{(1.13)\ (10,000)}{(100)(75)} = (1.356)\ (1.33) =$$

$$P.U.R = (1.5) \times \frac{(.83)\ (10,000)}{(100)(75)} = (1.245)\ (1.33) =$$

$$P.U.X = \frac{(.00008)\ (10,000)^*}{1000\ \ (.120)^2} = (.00008)\ (694.44) =$$

	P.U.R	P.U.X
P.U.X (1Ø)		.2000
P.U.X (Transformer)		1.8035
P.U.R (Transformer)	1.6559	
P.U.X (Switch)		.0556
Total P.U.R & P.U.X =	1.6559	2.0591

$$\text{Total P.U.Z} = \sqrt{(1.6559)^2 + (2.0591)^2} = 2.6423$$

$$\underline{\text{Line to Neutral S.C. Sym RMS Amps @ 120 Volts}} = \frac{10,000}{.120\ (2.6423)} = \frac{83333}{(2.6423)} = \underline{31,540 \text{ Amps}}$$

Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

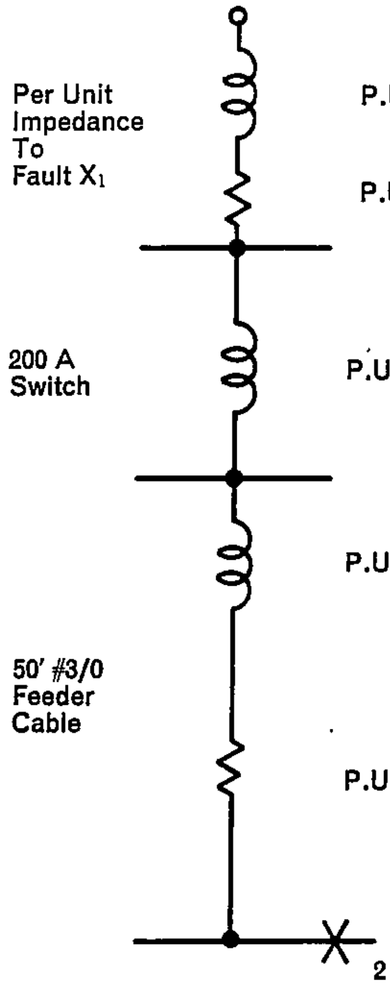
*The multiplier of two (2) is not applicable since on a line to neutral fault only one switch pole is involved.

LINE TO LINE FAULT @ 240 VOLTS

SINGLE PHASE TRANSFORMER
PER UNIT METHOD
1 Ø SHORT-CIRCUIT CALCULATION — FAULT X_2

10,000 KVA Base

IMPEDANCE DIAGRAM



$$P.U.X = 1.7307$$

$$P.U.R = 1.1039$$

$$P.U.X = (2)\ X\ \frac{(.0001)\ (10{,}000)}{(1000)\ \ (.240)^2} = 2\ (.0001)\ (173.61) =$$

$$P.U.X = 2\ X\left[\left(\frac{50'}{1000'}\right)\left(.0519\right)\right]X\ \frac{10000}{(1000)\ (.240)^2}$$
$$= 2(.05)\ (.0519)\ (173.61) =$$

$$P.U.R = 2\ X\left[\left(\frac{50'}{1000'}\right)\left(.0805\right)\right]X\ \frac{10{,}000}{(1000)\ (.240)^2}$$
$$= 2\ (.05)\ (.0805)\ (173.61) =$$

	P.U.R	P.U.X
P.U.X = 1.7307		1.7307
P.U.R = 1.1039	1.1039	
200 A Switch		.0347
50′ #3/0 Feeder Cable (X)		.9010
50′ #3/0 Feeder Cable (R)	1.3976	
Total P.U.R & P.U.X =	2.5015	2.6664

$$\text{Total P.U.Z} = \sqrt{(2.5015)^2 + (2.6664)^2} = 3.6561$$

$$\underline{\text{Line to Line S.C. Sym RMS Amps @ 240 Volts}} = \frac{10{,}000}{.240\ (3.6561)} = \frac{41667}{(3.6561)} = \underline{11{,}400\ \text{Amps}}$$

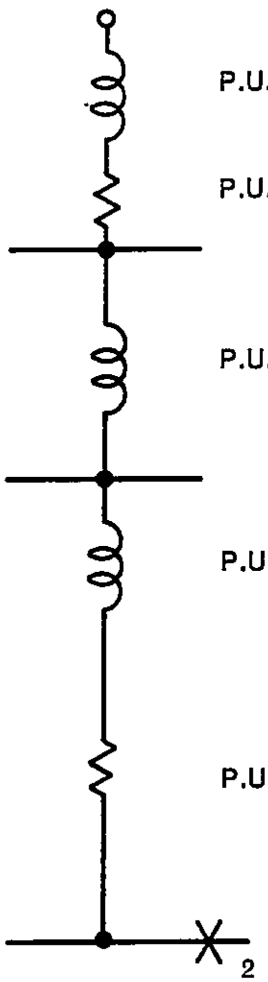
Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

LINE TO NEUTRAL FAULT @ 120 V

SINGLE PHASE TRANSFORMER
PER UNIT METHOD
1 ∅ SHORT-CIRCUIT CALCULATION — FAULT X_2

IMPEDANCE DIAGRAM

10,000 KVA Base



		P.U.R	P.U.X
Per Unit Impedance To Fault X_1	P.U.X = 2.0591		2.0591
	P.U.R = 1.6559	1.6559	
200 A Switch	$P.U.X = \frac{(.0001)\ (10{,}000)^{*}}{1000\ (.120)^2} = (.0001)\ (694.44) =$		.0694
50′ #3/0 Feeder Cable	$P.U.X = 2\ X\left[\left(\frac{50'}{1000'}\right)\left(.0519\right)\right]^{**} X \frac{10000}{(1000)\ (.120)^2}$ $= 2(.05)\ (.0519)\ (694.44) =$		3.6041
	$P.U.R = 2\ X\left[\left(\frac{50'}{1000'}\right)\left(.0805\right)\right]^{**} X \frac{10000}{(1000)\ (.120)^2}$ $= 2\ (.05)\ (.0805)\ (694.44) =$	5.5902	
	Total P.U.R & P.U.X =	7.2461	5.7326

$$\text{Total P.U.Z} = \sqrt{(7.2461)^2 + (5.7326)^2} = 9.2395$$

$$\underline{\text{Line to Neutral S.C. Sym RMS Amps @ 120 Volts}} = \frac{10{,}000}{(.120)\ (9.2395)} = \frac{83333}{9.2395} = \underline{9{,}020 \text{ Amps}}$$

Note: See P. 35 "Data Section" for impedance data for the electrical components and P. 18-20 for the per unit constants.

*The multiplier of two (2) is not applicable since on a line-to-neutral fault only one switch pole is involved.

**Assuming the neutral conductor and line conductor are the same size.

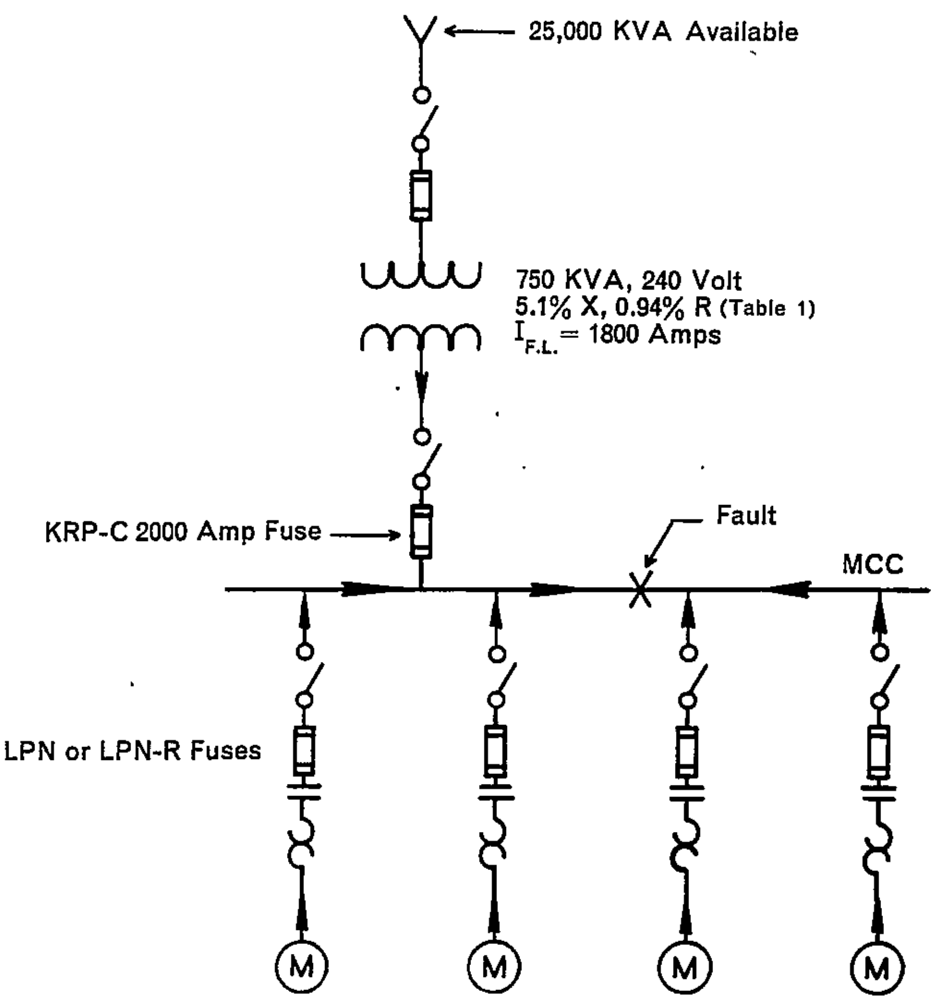
EFFECT OF LOW AVAILABLE UTILITY KVA

Even when utility fault currents are held down to a low level, it is not always safe to specify protective devices with limited interrupting capacity.

Over night the available fault KVA which the utility can deliver might be doubled or tripled. Since the destructive thermal and magnetic forces vary as the square of the current, any increase in fault level could result in a disastrous situation. The protective device selected should be one that takes system growth into consideration.

System B points out that despite a very limited utility short-circuit KVA, there is considerable short-circuit current available and any future increase in the utility system will result in even more fault current.

SYSTEM B

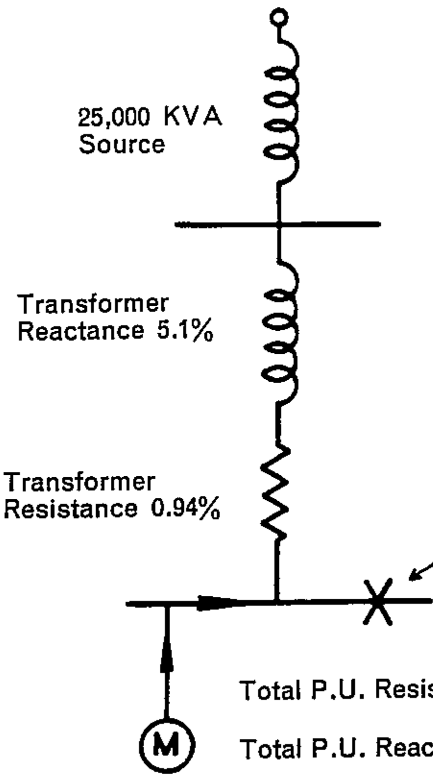


NOTE: Since the transformer supplies this particular motor control center directly, we assume that bus and cable impedances are negligible compared to source and transformer impedances.

3 ∅ SHORT-CIRCUIT CALCULATION — SYSTEM B

10,000 KVA Base — Per-Unit Method

IMPEDANCE DIAGRAM



$P.U.X_{SO} = 0.4000$ (Table A, Page 19)

$P.U.X_{TR} = (5.1)(.1333) = 0.6800$ (Table B, Page 19)

$P.U.R_{TR} = (0.94)(.1333) = 0.1250$ (Table B, Page 19)

P.U.R	P.U.X
	0.4000
	0.6800
0.1250	
0.1250	1.0800

Total P.U. Resistance = 0.1250 ohms

Total P.U. Reactance = 1.0800 ohms

Total P.U. Impedance = $\sqrt{(0.1250)^2 + (1.0800)^2} = 1.0850$

Symmetrical rms short-circuit current = $\frac{24,039}{1.0850} = 22,150$ Amps. (Table D, Page 20)

Asym Motor Contribution (100%) = 5 x transformer full load Amps. = 5 x 1800 = 9,000 Amps.

Sym Motor Contribution = $\frac{9,000}{1.25} = 7200$ Amps.

Total symmetrical rms short-circuit current = 22,150 + 7200 = 29,350 Amps.

X/R ratio = 1.08/0.125 = 8.64

Asymmetrical Factor* = 1.40

Asymmetrical rms short-circuit current = 1.40 x 22,150 = 31,000

Total asymmetrical rms short-circuit current = 9000 + 31,000 = 40,000 Amps.

NOTE: Properly selected dual-element current-limiting fuses in motor control center would clear short-circuit in less than ¼ cycle and coordinate selectively with the KRP-C 2000 ampere main fuses.

*Multiplier for maximum 1-phase rms amperes at ½ cycle.

GENERAL DISCUSSIONS
OF
SHORT-CIRCUIT CALCULATIONS

(A) MOTOR CONTRIBUTION

When an electrical system is short-circuited, synchronous and induction motors will feed additional short-circuit current to the fault at a value approximately equal to their locked rotor rating. In the preceding example the locked rotor current rating is assumed to be five times the motor full load current. This is a conservative figure and on the safe side. Actual contribution would normally be somewhat less.

(B) LIMITING FAULT CURRENT

The asymmetrical short-circuit current will continue to flow for several cycles depending upon the X/R ratio of the system. The asymmetrical fault current will eventually decay to the final symmetrical value of current which we calculated in the examples. Since the asymmetrical current is always greater than the symmetrical current, we find that the largest amount of destructible energy flows during the first several cycles after the fault is initiated. The amount of destructive energy is proportional to the square of the current so we can see that it is very important to limit the current to as small a value as possible by introducing proper interrupting means.

In system-A, Page 5, the 60 ampere LOW-PEAK dual-element fuse in the motor control center would limit a 30,530 ampere symmetrical fault to a value equivalent to less than 2500 amperes rms, clearing the fault in less than ¼ cycle.

DATA SECTION

This section contains tables conveniently arranged to facilitate short-circuit calculations.

INDEX TO DATA SECTION TABLES

Table 1—TRANSFORMER IMPEDANCE DATA*

Percent R, X and Z based on Transformer KVA.

Transformer Rating KVA	X/R	R %	X %	Z %
150	3.24	1.23	4.0	4.19
225	3.35	1.19	4.0	4.17
300	3.50	1.14	4.0	4.16
500	3.85	1.04	4.0	4.12
750	5.45	0.94	5.1	5.19
1000	5.70	0.89	5.1	5.19
1500	6.15	0.83	5.1	5.18
2000	6.63	0.77	5.1	5.17
150	1.5	1.111	1.665	2.0
225	1.5	1.111	1.665	2.0
300	1.5	1.111	1.665	2.0
500	1.5	1.111	1.665	2.0

NOTE 1: These values are for three-phase, liquid filled, self-cooled transformers.

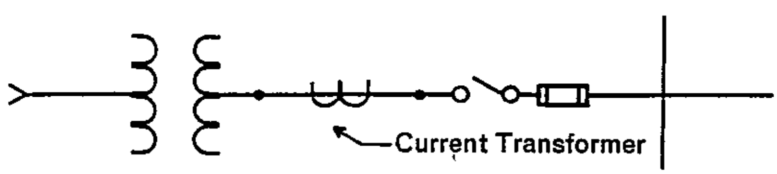
NOTE 2: Due to the trend toward lower impedance transformers for better voltage regulation, the actual transformer impedance may deviate from the NEMA Standard given at left. Therefore, for actual values, obtain nameplate impedance from owner or manufacturer. The percent X and percent R values are desirable for calculation.

*Table reprinted with permission of NEMA, Table A-1, Pub. No. AB 1-1969.

Table 2—CURRENT TRANSFORMER REACTANCE DATA

APPROXIMATE REACTANCES OF CURRENT TRANSFORMERS*

Primary Current Ratings — Amperes	Reactance in Ohms for Various Voltage Ratings		
	600-5000V	7500V	15,000V
100-200	0.0022	0.0040	
250-400	0.0005	0.0008	0.0002
500-800	0.00019	0.00031	0.00007
1000-4000	0.00007	0.00007	0.00007



NOTE: Values given are in ohms per phase. For actual values, refer to manufacturer's data.

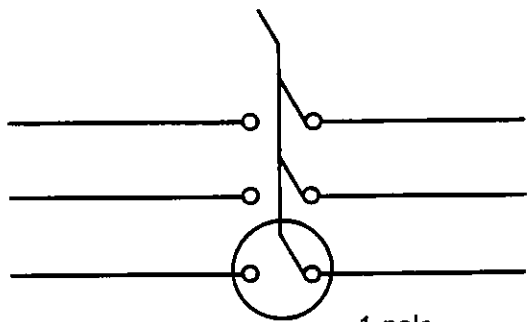
*Reprinted with permission of I.E.E.E., "Electric Power Distribution for Industrial Plants," I.E.E.E. No. 141, Oct. 1964, pg. 98.

Table 3—DISCONNECTING SWITCH REACTANCE DATA

The reactance of disconnecting switches for low-voltage circuits (600 volts and below) is in the order of magnitude of 0.00008 ohms per pole to 0.00005 ohms per pole at 60 cycles for switches rated 400-4000 amperes respectively.*

APPROXIMATE REACTANCES**

Switch Size (Amps)	X (Ohms)
200	0.0001
400	0.00008
600	0.00008
800	0.00007
1200	0.00007
1600	0.00005
2000	0.00005
3000	0.00004
4000	0.00004



*Reprinted with permission of I.E.E.E., Ibid.

**For actual values, refer to manufacturer's data.

Table 4—CIRCUIT BREAKER REACTANCE DATA

REACTANCE OF LOW-VOLTAGE POWER CIRCUIT BREAKERS†

Breaker Interrupting Rating — Amperes	Ampere Rating	Reactance in Ohms
15,000 and 25,000	15 to 35	0.04
	50 to 100	0.004
	125 to 225	0.001
	250 to 600	0.0002
50,000	200 to 800	0.0002
	1000 to 1600	0.00007
75,000	2000 to 3000	0.00008
100,000	4000	0.00008

NOTE: Due to the method of rating low-voltage power circuit breakers, the reactance of the breaker which is to interrupt the fault is not included in calculating fault current.†

TYPICAL MOLDED CASE CIRCUIT BREAKER IMPEDANCES††

Molded Case Breaker Ampere Rating	Resistance in Ohms	Reactance in Ohms
20	.00700	Negligible
40	.00240	Negligible
100	.00200	.00070
225	.00035	.00020
400	.00031	.00039
600	.00007	.00017

NOTE: Above 600 amperes the reactances of molded case breakers are similar to those given in the Low-Voltage Power Circuit Breaker Table above.

†Reprinted with permission of I.E.E.E., Ibid.

††For actual values, consult manufacturer. These values will vary with manufacturer and design.

Table 5—COPPER CABLE IMPEDANCE DATA*
OHMS PER 1000 FEET

Resistance, Reactance and Impedance of Copper Cable Circuits

Three Single Conductors

AWG or MCM	In Magnetic Duct						In Nonmagnetic Duct					
	600 V and 5 kv Nonshielded			5 kv Shielded and 15 kv			600 V and 5 kv Nonshielded			5 kv Shielded and 15 kv		
	R	X	Z	R	X	Z	R	X	Z	R	X	Z
8	.811	.0754	.814	.811	.0860	.816	.811	.0603	.813	.811	.0688	.814
8 (solid)	.786	.0754	.790	.786	.0860	.791	.786	.0603	.788	.786	.0688	.789
6	.510	.0685	.515	.510	.0796	.516	.510	.0548	.513	.510	.0636	.514
6 (solid)	.496	.0685	.501	.496	.0796	.502	.496	.0548	.499	.496	.0636	.500
4	.321	.0632	.327	.321	.0742	.329	.321	.0506	.325	.321	.0594	.326
4 (solid)	.312	.0632	.318	.312	.0742	.321	.312	.0506	.316	.312	.0594	.318
2	.202	.0585	.210	.202	.0685	.214	.202	.0467	.207	.202	.0547	.209
1	.160	.0570	.170	.160	.0675	.174	.160	.0456	.166	.160	.0540	.169
1/0	.128	.0540	.139	.128	.0635	.143	.127	.0432	.134	.128	.0507	.138
2/0	.102	.0533	.115	.103	.0630	.121	.101	.0426	.110	.102	.0504	.114
3/0	.0805	.0519	.0958	.0814	.0605	.101	.0766	.0415	.0871	.0805	.0484	.0939
4/0	.0640	.0497	.0810	.0650	.0583	.0929	.0633	.0398	.0748	.0640	.0466	.0792
250	.0552	.0495	.0742	.0557	.0570	.0797	.0541	.0396	.0670	.0547	.0456	.0712
300	.0464	.0493	.0677	.0473	.0564	.0736	.0451	.0394	.0599	.0460	.0451	.0644
350	.0378	.0491	.0617	.0386	.0562	.0681	.0368	.0393	.0536	.0375	.0450	.0586
400	.0356	.0490	.0606	.0362	.0548	.0657	.0342	.0392	.0520	.0348	.0438	.0559
450	.0322	.0480	.0578	.0328	.0538	.0630	.0304	.0384	.0490	.0312	.0430	.0531
500	.0294	.0466	.0551	.0300	.0526	.0605	.0276	.0373	.0464	.0284	.0421	.0508
600	.0257	.0463	.0530	.0264	.0516	.0580	.0237	.0371	.0440	.0246	.0412	.0479
750	.0216	.0445	.0495	.0223	.0497	.0545	.0194	.0356	.0405	.0203	.0396	.0445

Three-Conductor Cable

AWG or MCM	In Magnetic Duct and Steel Interlocked Armor						In Nonmagnetic Duct and Aluminum Interlocked Armor					
	600 v and 5 kv Nonshielded			5 kv Shielded and 15 kv			600 v and 5 kv Nonshielded			5 kv Shielded and 15 kv		
	R	X	Z	R	X	Z	R	X	Z	R	X	Z
8	.811	.0577	.813	.811	.0658	.814	.811	.0503	.812	.811	.0574	.813
8 (solid)	.786	.0577	.788	.786	.0658	.789	.786	.0503	.787	.786	.0574	.788
6	.510	.0525	.513	.510	.0610	.514	.510	.0457	.512	.510	.0531	.513
6 (solid)	.496	.0525	.499	.496	.0610	.500	.496	.0457	.498	.496	.0531	.499
4	.321	.0483	.325	.321	.0568	.326	.321	.0422	.324	.321	.0495	.325
4 (solid)	.312	.0483	.316	.312	.0508	.317	.312	.0422	.315	.312	.0495	.316
2	.202	.0448	.207	.202	.0524	.209	.202	.0390	.206	.202	.0457	.207
1	.160	.0436	.166	.160	.0516	.168	.160	.0380	.164	.160	.0450	.166
1/0	.128	.0414	.135	.128	.0486	.137	.127	.0360	.132	.128	.0423	.135
2/0	.102	.0407	.110	.103	.0482	.114	.101	.0355	.107	.102	.0420	.110
3/0	.0805	.0397	.0898	.0814	.0463	.0936	.0766	.0346	.0841	.0805	.0403	.090
4/0	.0640	.0381	.0745	.0650	.0446	.0788	.0633	.0332	.0715	.0640	.0389	.0749
250	.0552	.0379	.0670	.0557	.0436	.0707	.0541	.0330	.0634	.0547	.0380	.0666
300	.0464	.0377	.0598	.0473	.0431	.0640	.0451	.0329	.0559	.0460	.0376	.0596
350	.0378	.0373	.0539	.0386	.0427	.0576	.0368	.0328	.0492	.0375	.0375	.0530
400	.0356	.0371	.0514	.0362	.0415	.0551	.0342	.0327	.0475	.0348	.0366	.0505
450	.0322	.0361	.0484	.0328	.0404	.0520	.0304	.0320	.0441	.0312	.0359	.0476
500	.0294	.0349	.0456	.0300	.0394	.0495	.0276	.0311	.0416	.0284	.0351	.0453
600	.0257	.0343	.0429	.0264	.0382	.0464	.0237	.0309	.0389	.0246	.0344	.0422
750	.0216	.0326	.0391	.0223	.0364	.0427	.0197	.0297	.0355	.0203	.0332	.0389

Resistance based on tinned copper at 60 cycles. 600 volt and 5 kv unshielded based on varnished cambric insulation. 5 kv shielded and 15 kv cable based on Neoprene insulation. Values shown are for 1000 feet of cable at 75 C.

*Reprinted from "Actual Specifying Engineer," October, 1965.

Table 6—ALUMINUM CABLE IMPEDANCE DATA*
APPROXIMATE OHMS PER 1000 FEET

Cross-Linked Polyethylene Insulated Cable Resistance, Reactance and Impedance Aluminum Conductor Cable

Three Single Conductors.

AWG or MCM	In Magnetic Duct						In Nonmagnetic Duct					
	600 V and 5kv Nonshielded			5 kv Shielded and 15 kv			600 V and 5 kv Nonshielded			5 kv Shielded and 15 kv		
	R	X	Z	R	X	Z	R	X	Z	R	X	Z
6	.847	.053	.849	—	—	—	.847	.042	.848	—	—	—
4	.532	.050	.534	.532	.068	.536	.532	.040	.534	.532	.054	.535
2	.335	.046	.338	.335	.063	.341	.335	.037	.337	.335	.050	.339
1	.265	.048	.269	.265	.059	.271	.265	.035	.267	.265	.047	.269
1/0	.210	.043	.214	.210	.056	.217	.210	.034	.213	.210	.045	.215
2/0	.167	.041	.172	.167	.055	.176	.167	.033	.170	.167	.044	.173
3/0	.133	.040	.139	.132	.053	.142	.133	.037	.137	.132	.042	.139
4/0	.106	.039	.113	.105	.051	.117	.105	.031	.109	.105	.041	.113
250	.0896	.0384	.0975	.0892	.0495	.102	.0894	.0307	.0945	.0891	.0396	.0975
300	.0750	.0375	.0839	.0746	.0479	.0887	.0746	.0300	.0804	.0744	.0383	.0837
350	.0644	.0369	.0742	.0640	.0468	.0793	.0640	.0245	.0705	.0638	.0374	.0740
400	.0568	.0364	.0675	.0563	.0459	.0726	.0563	.0291	.0634	.0560	.0367	.0700
500	.0459	.0355	.0580	.0453	.0444	.0634	.0453	.0284	.0535	.0450	.0355	.0573
600	.0388	.0359	.0529	.0381	.0431	.0575	.0381	.0287	.0477	.0377	.0345	.0511
700	.0338	.0350	.0487	.0332	.0423	.0538	.0330	.0280	.0433	.0326	.0338	.0470
750	.0318	.0341	.0466	.0310	.0419	.0521	.0309	.0273	.0412	.0304	.0335	.0452
1000	.0252	.0341	.0424	.0243	.0414	.0480	.0239	.0273	.0363	.0234	.0331	.0405

Three-Conductor Cables

AWG or MCM	In Magnetic Duct						In Nonmagnetic Duct					
	600 V and 5kv Nonshielded			5 kv Shielded and 15 kv			600 V and 5 kv Nonshielded			5 kv Shielded and 15 kv		
	R	X	Z	R	X	Z	R	X	Z	R	X	Z
6	.847	.053	.849	—	—	—	.847	.042	.848	—	—	—
4	.532	.050	.534	—	—	—	.532	.040	.534	—	—	—
2	.335	.046	.338	.335	.056	.340	.335	.037	.337	.335	.045	.338
1	.265	.048	.269	.265	.053	.270	.265	.035	.267	.265	.042	.268
1/0	.210	.043	.214	.210	.050	.216	.210	.034	.213	.210	.040	.214
2/0	.167	.041	.172	.167	.049	.174	.167	.033	.170	.167	.039	.171
3/0	.133	.040	.139	.133	.048	.141	.133	.037	.137	.133	.038	.138
4/0	.106	.039	.113	.105	.045	.114	.105	.031	.109	.105	.036	.111
250	.0896	.0384	.0975	.0895	.0436	.100	.0894	.0307	.0945	.0893	.0349	.0959
300	.0750	.0375	.0839	.0748	.0424	.0860	.0746	.0300	.0804	.0745	.0340	.0819
350	.0644	.0369	.0742	.0643	.0418	.0767	.0640	.0245	.0705	.0640	.0334	.0722
400	.0568	.0364	.0675	.0564	.0411	.0700	.0563	.0291	.0634	.0561	.0329	.0650
500	.0459	.0355	.0580	.0457	.0399	.0607	.0453	.0284	.0535	.0452	.0319	.0553
600	.0388	.0359	.0529	.0386	.0390	.0549	.0381	.0287	.0477	.0380	.0312	.0492
700	.0338	.0350	.0487	.0335	.0381	.0507	.0330	.0280	.0433	.0328	.0305	.0448
750	.0318	.0341	.0466	.0315	.0379	.0493	.0309	.0273	.0412	.0307	.0303	.0431
1000	.0252	.0341	.0424	.0248	.0368	.0444	.0239	.0273	.0363	.0237	.0294	.0378

Values Are for 1000 Circuit Feet at 90°C Conductor

***Courtesy of Kaiser Aluminum Electrical Products Division**

Table 7 — BUSWAY IMPEDANCE DATA* — OHMS PER 1000 FEET

Plug-In Busway

Ampere Rating	Ohms per 1000 feet line to neutral 60 cycles		
	Resistance	Reactance	Impedance
Copper Bus Bars			
225	0.0836	0.0800	0.1157
400	0.0437	0.0232	0.0495
600	0.0350	0.0179	0.0393
800	0.0218	0.0136	0.0257
1000	0.0145	0.0135	0.0198

Ampere Rating	Ohms per 1000 feet line to neutral 60 cycles		
	Resistance	Reactance	Impedance
Aluminum Bus Bars			
225	0.1090	0.0720	0.1313
400	0.0550	0.0222	0.0592
600	0.0304	0.0121	0.0327
800	0.0243	0.0154	0.0288

Low-Impedance Feeder Busway

Ampere Rating	Ohms per 1000 feet line to neutral 60 cycles		
	Resistance	Reactance	Impedance
800	0.0219	0.0085	0.0235
1000	0.0190	0.0050	0.0196
1350	0.0126	0.0044	0.0134
1600	0.0116	0.0035	0.0121
2000	0.0075	0.0031	0.0081
2500	0.0057	0.0025	0.0062
3000	0.0055	0.0017	0.0058
4000	0.0037	0.0016	0.0040

Current Limiting Busway

Ampere Rating	Ohms per 1000 feet line to neutral 60 cycles			X/R Ratio
	Resistance	Reactance	Impedance	
1000	0.013	0.063	0.064	4.85
1350	0.012	0.061	0.062	5.08
1600	0.009	0.056	0.057	6.22
2000	0.007	0.052	0.052	7.45
2500	0.006	0.049	0.049	8.15
3000	0.005	0.046	0.046	9.20
4000	0.004	0.042	0.042	10.50

*Reprinted from "Actual Specifying Engineering," October, 1965.

Table 8 — ASYMMETRICAL FACTORS†

Short-circuit Power Factor, Percent	Short Circuit X/R Ratio	Ratio to Symmetrical Rms Amperes		
		Maximum 1-phase Instantaneous Peak Amperes Mp	Maximum 1-phase Rms Amperes at ½ Cycle M_m (Asymmetrical Factor)	Average 3-phase Rms Amperes at ½ Cycle M_a
0	∞	2.828	1.732	1.394
1	100.00	2.785	1.696	1.374
2	49.993	2.743	1.665	1.355
3	33.322	2.702	1.630	1.336
4	24.979	2.663	1.598	1.318
5	19.974	2.625	1.568	1.301
6	16.623	2.589	1.540	1.285
7	14.251	2.554	1.511	1.270
8	13.460	2.520	1.485	1.256
9	11.066	2.487	1.460	1.241
10	9.9301	2.455	1.436	1.229
11	9.0354	2.424	1.413	1.216
12	8.2733	2.394	1.391	1.204
13	7.6271	2.364	1.372	1.193
14	7.0721	2.336	1.350	1.182
15	6.5912	2.309	1.330	1.171
16	6.1695	2.282	1.312	1.161
17	5.7947	2.256	1.294	1.152

(Continued)

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Table 8 — ASYMMETRICAL FACTORS † (Con't.)

Short-circuit Power Factor, Percent	Short Circuit X/R Ratio	Ratio to Symmetrical Rms Amperes: Maximum 1-phase Instantaneous Peak Amperes Mp	Maximum 1-phase Rms Amperes at ½ Cycle M_m (Asymmetrical Factor)	Average 3-phase Rms Amperes at ½ Cycle M_a
18	5.4649	2.231	1.277	1.143
19	5.1672	2.207	1.262	1.135
20	4.8990	2.183	1.247	1.127
21	4.6557	2.160	1.232	1.119
22	4.4341	2.138	1.218	1.112
23	4.2313	2.11	1.205	1.105
24	4.0450	2.095	1.192	1.099
25	3.8730	2.074	1.181	1.093
26	3.7138	2.054	1.170	1.087
27	3.5661	2.034	1.159	1.081
28	3.4286	2.015	1.149	1.075
29	3.3001	1.996	1.139	1.070
30	3.1798	1.978	1.130	1.066
31	3.0669	1.960	1.121	1.062
32	2.9608	1.943	1.113	1.057
33	2.8606	1.926	1.105	1.053
34	2.7660	1.910	1.098	1.049
35	2.6764	1.894	1.091	1.046
36	2.5916	1.878	1.084	1.043
37	2.5109	1.863	1.078	1.039
38	2.4341	1.848	1.073	1.036
39	2.3611	1.833	1.068	1.033
40	2.2913	1.819	1.062	1.031
41	2.2246	1.805	1.057	1.028
42	2.1608	1.791	1.053	1.026
43	2.0996	1.778	1.049	1.024
44	2.0409	1.765	1.045	1.022
45	1.9845	1.753	1.041	1.020
46	1.9303	1.740	1.038	1.019
47	1.8780	1.728	1.034	1.017
48	1.8277	1.716	1.031	1.016
49	1.7791	1.705	1.029	1.014
50	1.7321	1.694	1.026	1.013
55	1.5185	1.641	1.015	1.008
60	1.3333	1.594	1.009	1.004
65	1.1691	1.553	1.004	1.002
70	1.0202	1.517	1.002	1.001
75	0.8819	1.486	1.0008	1.0004
80	0.7500	1.460	1.0002	1.00005
85	0.6198	1.439	1.00004	1.00002
100	0.0000	1.414	1.00000	1.00000

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SELECTIVE SYSTEMS
(Blackout Prevention)

Having determined the faults that must be interrupted, the next step is to specify Protective Devices that will provide a Selective System with proper Interrupting Capacity. . . . .

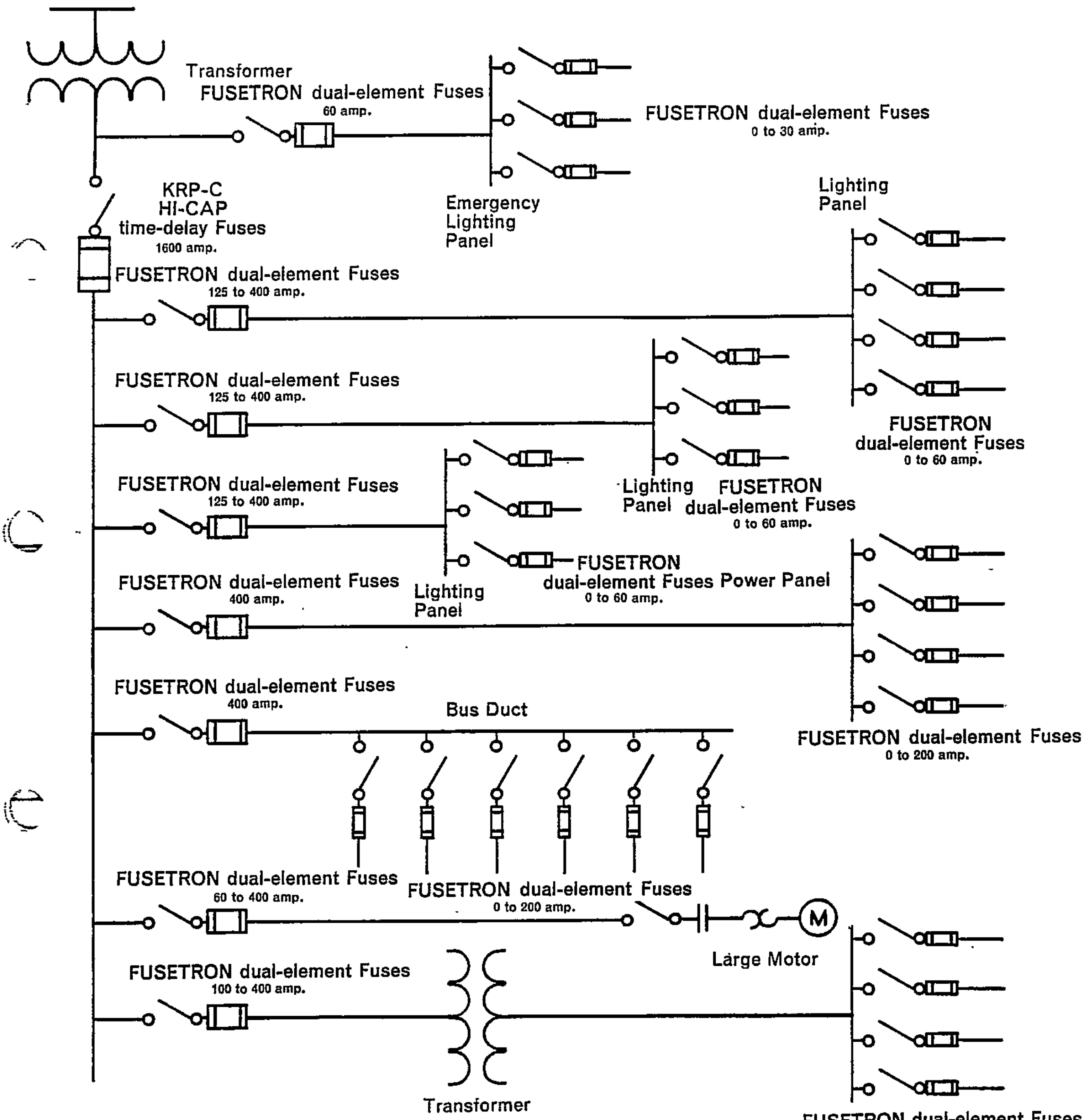
Such a system assures safety under all service conditions and prevents needless interruption of service on circuits other than the one on which a fault occurs.

The topic of Selectivity will be discussed in the next Handbook, Part II.

In order to prevent Blackouts some simple examples of selectively coordinated systems are shown on the following pages.

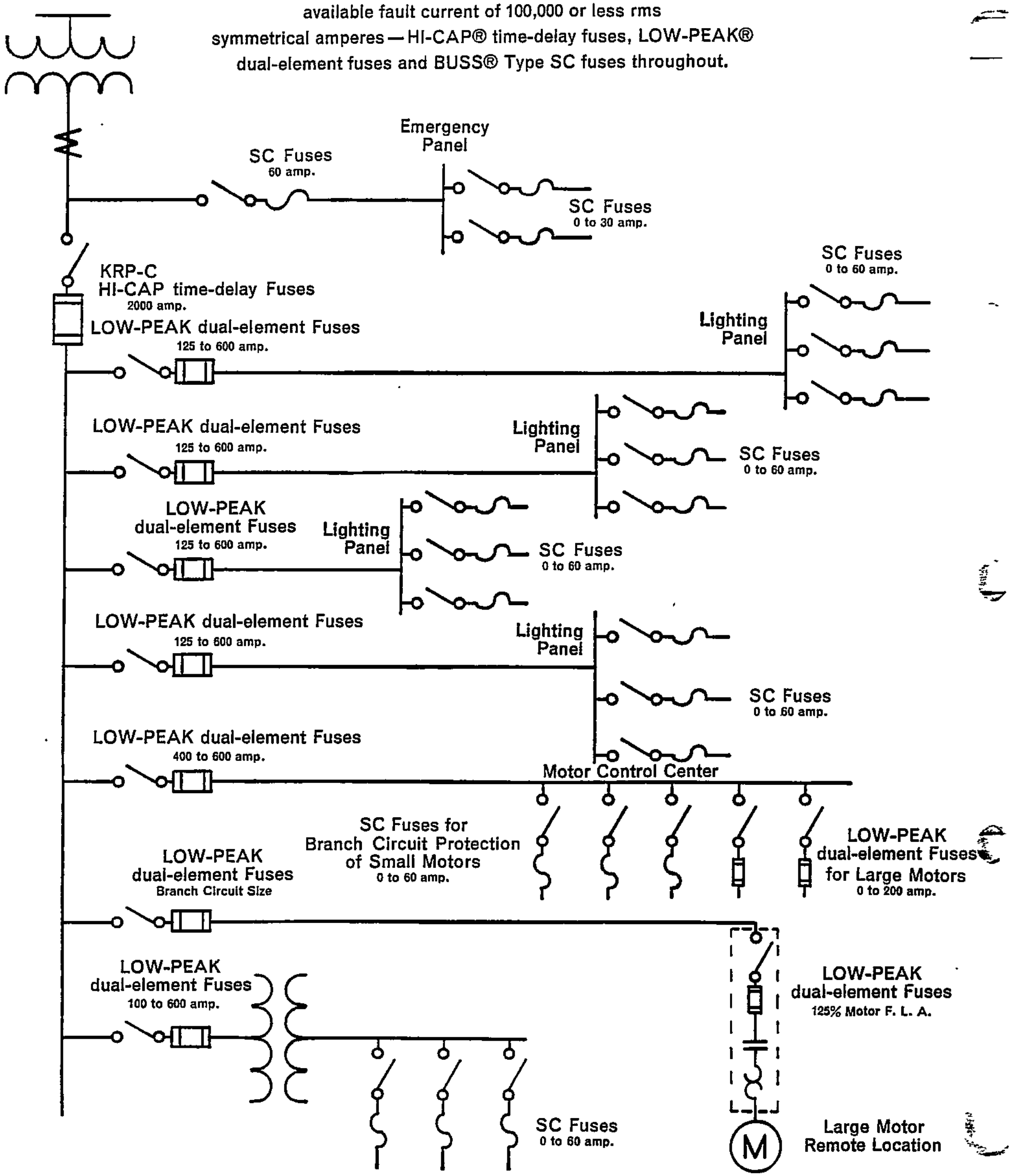
NOTE: The following systems also comply with Section 230-98 of the National Electrical Code — 1975 which requires adequate short-circuit rating of service equipment.

A SELECTIVE SYSTEM
for circuits of 600 volts or less —
having available fault current of 200,000 or less rms
symmetrical amperes — using HI-CAP® time-delay fuses
and FUSETRON® dual-element fuses throughout.

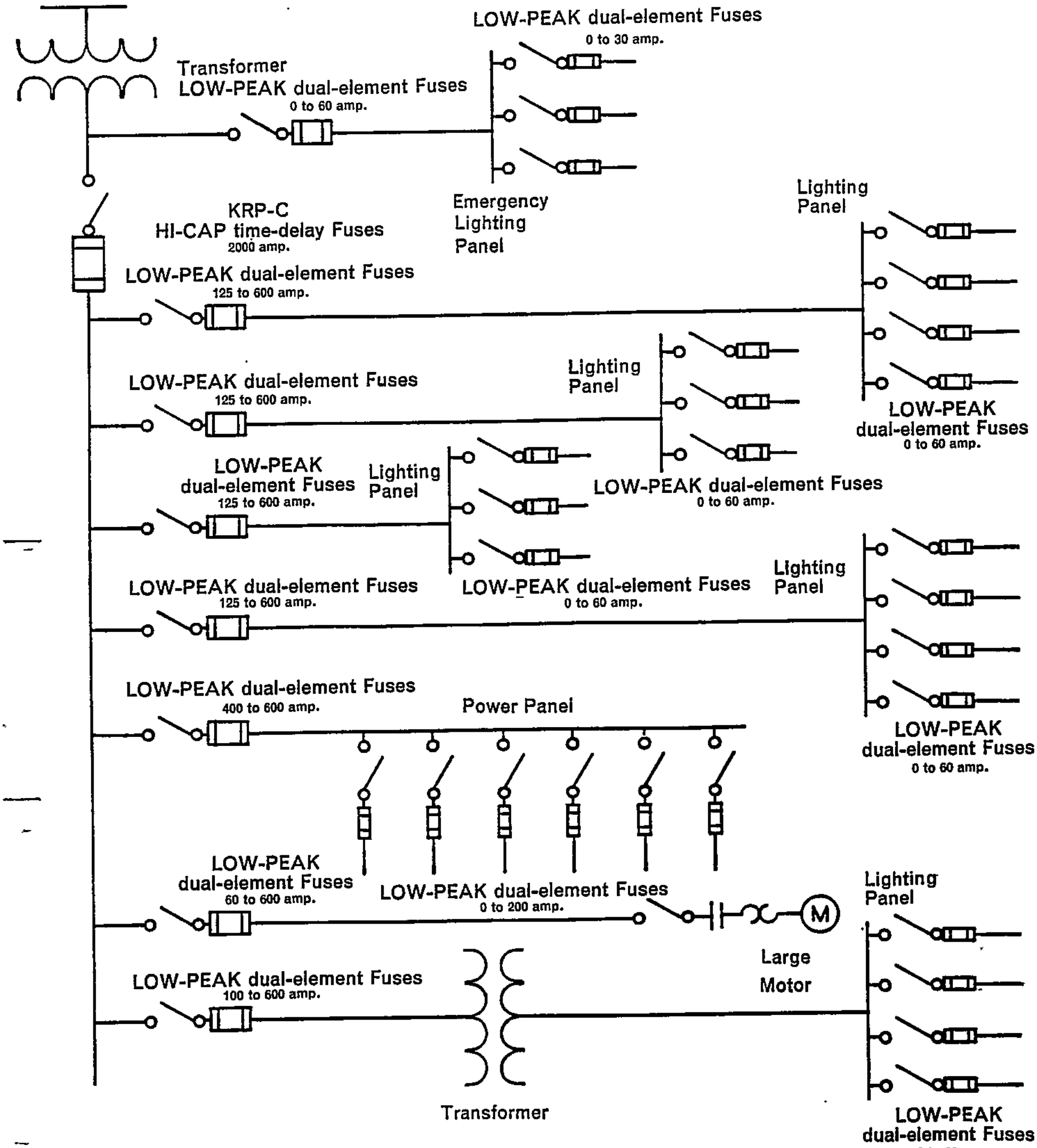


A SELECTIVE SYSTEM

For circuits of 277/480 volts or less having available fault current of 100,000 or less rms symmetrical amperes — HI-CAP® time-delay fuses, LOW-PEAK® dual-element fuses and BUSS® Type SC fuses throughout.

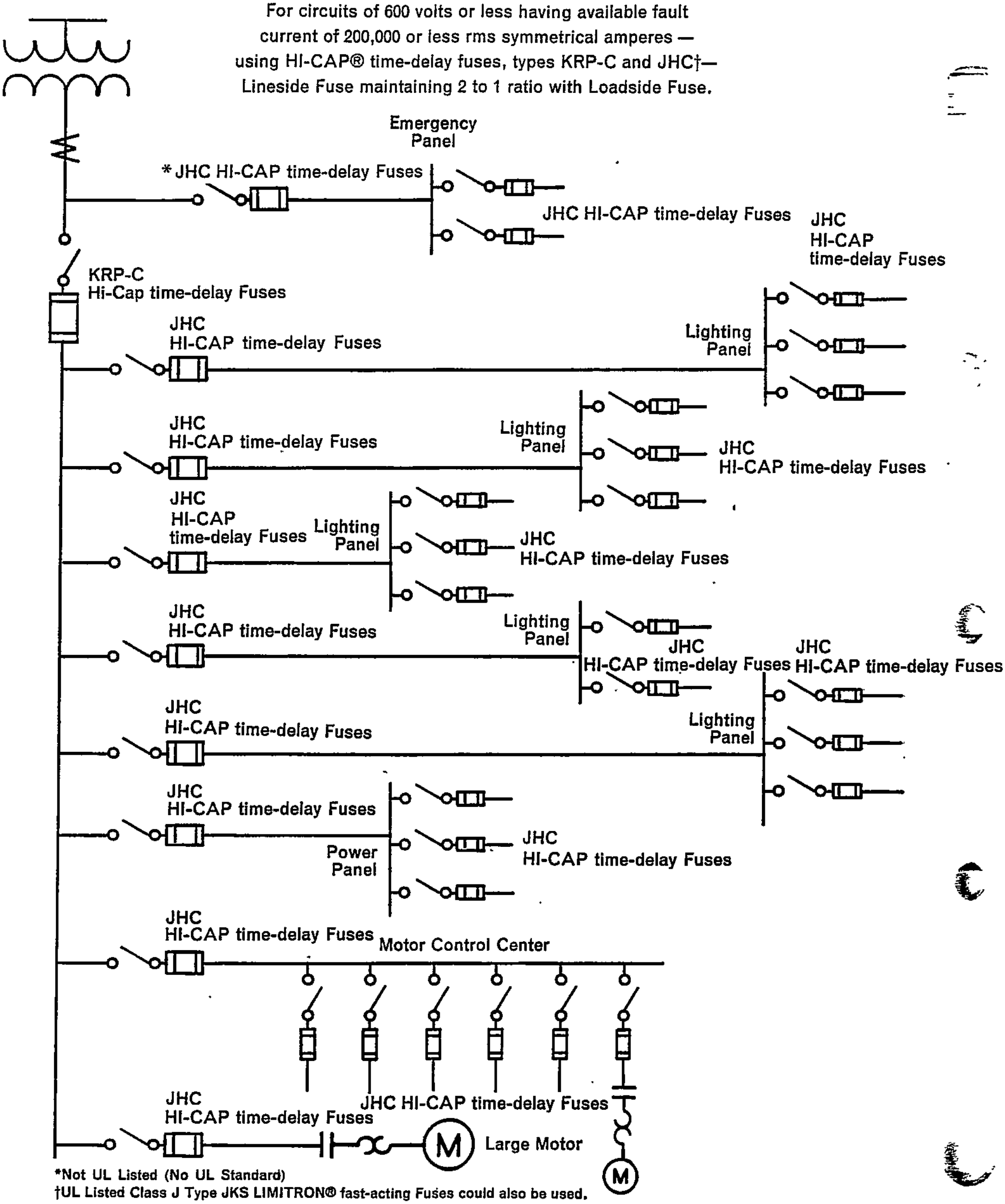


A SELECTIVE SYSTEM
for circuits of 600 volts or less —
having available fault current of 200,000 or less rms
symmetrical amperes — using HI-CAP® time-delay fuses and
LOW-PEAK® dual-element fuses throughout.



A SELECTIVE SYSTEM

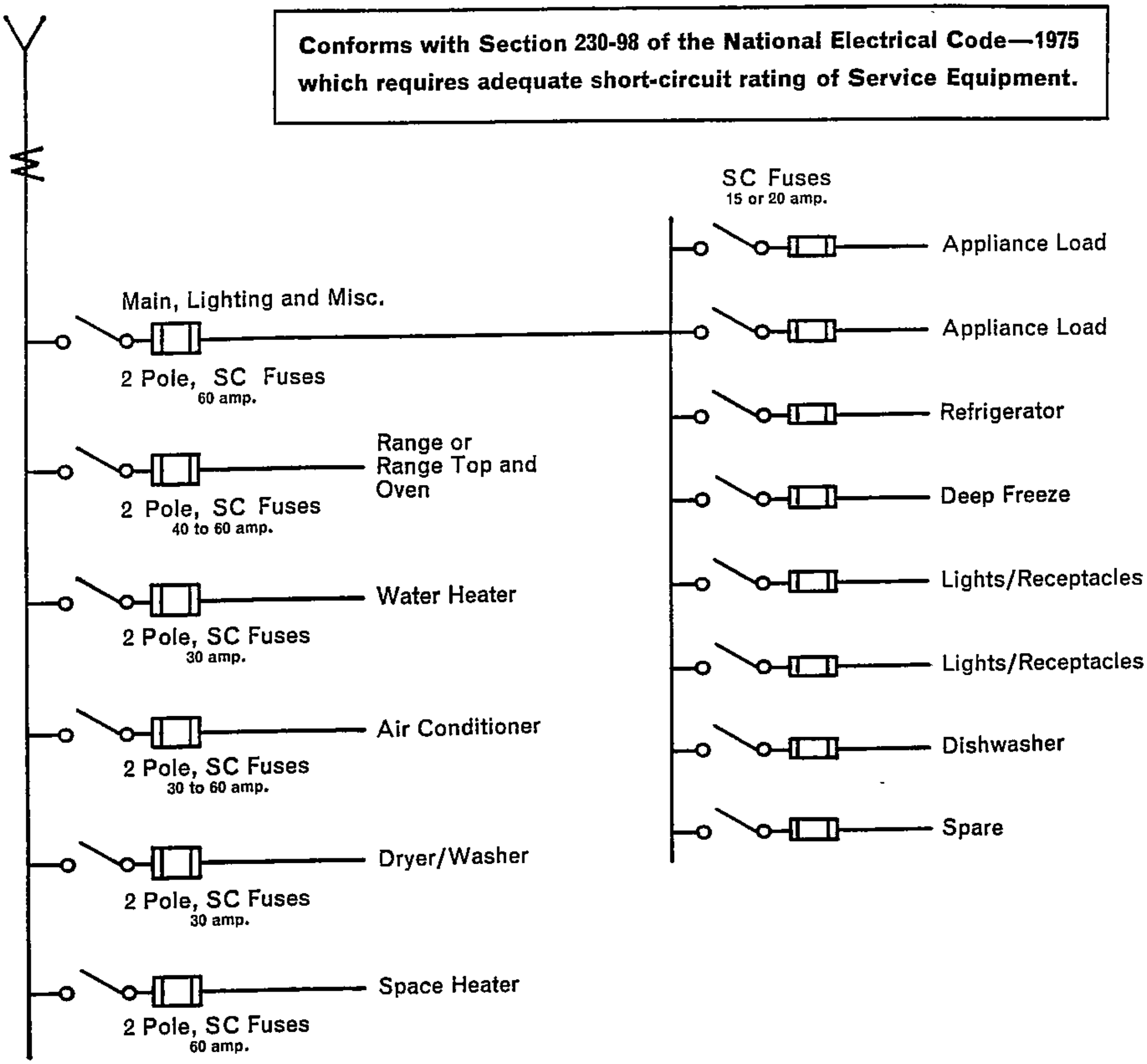
For circuits of 600 volts or less having available fault current of 200,000 or less rms symmetrical amperes — using HI-CAP® time-delay fuses, types KRP-C and JHC†— Lineside Fuse maintaining 2 to 1 ratio with Loadside Fuse.



*Not UL Listed (No UL Standard)
†UL Listed Class J Type JKS LIMITRON® fast-acting Fuses could also be used.

A SELECTIVE SYSTEM
for circuits of 115/230 volts or less — having available fault current of 100,000 or less rms symmetrical amperes — using BUSS® Type SC, size limiting fuses for protection of Residential and Small Commercial circuits.

Conforms with Section 230-98 of the National Electrical Code—1975 which requires adequate short-circuit rating of Service Equipment.



NOTE: FUSE PANELS AND LOAD CENTERS ARE AVAILABLE for BUSS Type SC FUSES THAT FEATURE:

1. Neon light, fuse out indicator
2. Safety, switch must be off to remove fuse
3. Size limiting, larger fuse cannot be put in smaller holder.
4. Cool operating
5. 100,000 amps. rms interrupting capacity rating
6. Time delay